Response to referee comments

Multi-modal sensing drifters as a tool for repeatable glacial hydrology flow path measurements

Andreas Alexander[1,2], Maarja Kruusmaa[3,5], Jeffrey A. Tuhtan[3], Andrew J. Hodson[2,4], Thomas V. Schuler[1,2], Andreas Kääb[1]

[1]Department of Geosciences, University of Oslo, 0316 Oslo, Norway
[2]Department of Arctic Geology, The University Centre in Svalbard, 9171 Longyearbyen, Norway
[3]Centre for Biorobotics, Tallinn University of Technology, 12618 Tallinn, Estonia
[4]Department of Environmental Sciences, Western Norway University of Applied Sciences, 6856 Sogndal, Norway
[5]Centre for Autonomous Marine Operations and Systems, Norwegian University of Science and Technology, 7491 Trondheim, Norway

Correspondence to: Andreas Alexander (andreas.alexander@geo.uio.no)

We would like to thank the reviewers for their constructive feedback and valuable input that certainly helped to improve this manuscript. The manuscript has been shortened considerable. All figures have been revised to improve readability. The detailed responses to the reviewer comments are presented below. A mark-up version of the manuscript, showing the changes made in response to the referee's comments follows thereafter.

Response to RC 1

We would like to thank Elizabeth Bagshaw for reviewing our manuscript and providing helpful and constructive feedback, which helped to improve our manuscript. In the following we respond to the comments and outline how we addressed these in the revision of the manuscript. Referee comments are presented in *italic*, and our replies follow directly thereafter.

General changes

All figures are revised to improve readability, and annotations have been added to label the step-pool examples. The introduction has been substantially revised and includes new references pertaining to supraglacial systems as well as for oceanographic / river drifters.

General comments

This paper gives a comprehensive account of a challenging experiment to assess the repeatability and usability of data collected by a drifting sensor. It should be noted that experiments including field testing of new engineering techniques in extreme environments are exceptionally challenging, and the authors should be congratulated on their successful deployment. The paper is well-written, and gives a comprehensive review of much of the supporting literature.

Thank you for this positive overall judgment.

However, the scope of the paper is somewhat confusing to the reader, since the problem is framed as a subglacial experiment, yet the data are confined to the supraglacial environment. This in no way invalidates the results, but I believe that the paper would be more appealing to the target audience if the supraglacial scope were made clear from the first paragraph and in the abstract. The subglacial deployment may be the ultimate goal of the project, but the current state of the science and engineering is limited to the supraglacial. I advise that the introductory paragraphs and abstract are focussed on supraglacial literature, with some additional references as necessary (for example, Decaux et al 2019 cited later). The subglacial material can then be moved to later in the discussion, to make clear how the supraglacial results can be utilised and developed in the future.

We reworked the abstract and the introduction to make the scope of the study more clear. We additionally added further references related to supraglacial systems, and reduced the focus on subglacial investigations.

I like the use of statistics to validate the sensor performance, and the realism in relating the statistical results to logistical practicality. However, the actual purpose of the paper is not entirely clear in this iteration – is it an engineering test, a sensor validation exercise, or does it reveal a previously unknown glaciological phenomenon? All of these are valid outcomes, but the introduction and particularly the abstract should be better focused to demonstrate that experimental purpose to the reader. The paper could also be shortened by moving some of the tables to supplementary info (see below).

We shortened the manuscript and clarified the scope of the work and research objectives.

Specific comments

Figure 1: please could you include a labelled photo of the sensors? It would be great to see them in a bit more detail

We added an additional figure (figure 2), illustrating the sensor components in greater detail.

Figure 2: Place names are illegible on the map, and the features of the glacier need some labels in c).

We changed the map in a) and added additional labels and pictures in c).

It would be useful to know where the net was situated, for example, and perhaps have some accompanying photos of the deployment/recovery sites.

Added to the figure in c).

Could you comment on the feasibility of the net recovery in a larger system, and if the sensors are destined for the subglacial system, on the robustness of the net methods with debris and bedload transport in the flow?

We added a comment about the net recovery in the Discussion part of our improved version of the manuscript (P19 L17-22).

Table 1: Could transmission distance (if relevant) be a separate column rather than a comment?

Transmission distance is only mentioned once in the comment for the Smeets et al. (2012) reference. Making a separate column would therefore leave the majority of entries empty for the other references. So we would prefer to leave it as it is. We however moved this table to the supplementary material.

P3, L23: Is 500 Euro truly low cost? This is a subjective term.

We removed it.

P10, L20: Please include an estimate of the range of discharge variability

We did not measure it, so any estimation would be speculative. We added an according comment (P9, L6).

Figure 3 doesn't really add much to the paper, it could be removed to save space without detriment, since the workflow is not unusual and is described in the text

Removed.

P12, L25: please define the 'features of subglacial channels'

We added additional information (P10, L29-30).

Figure 4 and Tables 3 and 5 may be better placed in supplementary info, since their content is only of interest to a very specific audience and the paper is rather long

Moved to the supplementary information.

Table 4 and P14, L7: what is the 'required size' for a subglacial deployment? Unclear how these measurements are extrapolated to the subglacial system: just because the drifter can move through an open supraglacial stream doesn't necessarily infer that it will pass through the subglacial environment

We added additional information to clarify (P11, L15-16).

Figure 10: Can other sensor data be added to this figure? It would be very useful to see the accelerometer data plotted alongside. The IMU accelerometer method is really exciting, so if the data could be demonstrated

alongside the pressure and photographs, it would really contribute something valuable to the field.

We added the accelerometer data to this figure (P18, F9). Additionally we also marked the step-pool sequence on the other plots (P15, F6; P16, F7; P17, F8).

P25, L11-25: What were you hoping to determine with this dataset? It seems that you have proven that the technology and the sensor set work (which is great!), so can you relate this to the flowpaths? How do the data relate to visual observations? If you hope to use this to visualize subglacial systems, then it is important to relate the sensor data (of which you have a considerable quantity) from the supraglacial system to visual observations where you can. Then you can demonstrate how this might be used in the subglacial environment. 'We need more data' seems a bit of a cop-out! What precision do you need to obtain scientifically useful data?

We added additional information to clarify this section (P19, L26-29).

P26, L26: What is 'satisfactory performance'? This is very subjective. What did this experiment hope to achieve, and did you do it? Was it field testing of the casing, the transport method, or of the sensor performance, or of the usefulness of the data to characterise the supraglacial flowpath? Or of future subglacial deployment? Please be specific – this is an excellent engineering test, but subjectivity in appraisal should be avoided.

Thank you for this comment, we went through the manuscript and removed subjective statements, and clarified the scope of the experiment.

Table 6 isn't terribly useful.

Agreed, the table has been removed.

Response to RC 2

We would like to thank Samuel Doyle for reviewing our manuscript and provide helpful and constructive feedback, which will helped to improve the manuscript. In the following we present our responses to the referee comments and how we addressed these in the revision of the manuscript. The referee comments are presented in bold and *italic*, our replies follow immediately thereafter.

General changes

All figures are revised to improve readability, and annotations have been added to label the step-pool example. The introduction has been substantially revised and includes new references pertaining to supraglacial systems as well as for oceanographic / river drifters.

Overall comments

Alexander et al. present a statistical assessment of the performance of a new sensing system – a Lagrangian drifter – for glacier hydrological experiments. They report results from repeated tests in a supraglacial channel and suggest (though never that directly) that there may be future potential for deploying the drifter within the subglacial environment. The sensor system is novel and this manuscript makes an important contribution to the very limited literature on Lagrangian drifters in glaciology.

We thank the reviewer for his positive judgment.

Although it is verbose, the paper is generally well-written.

We shortened the manuscript. See also the answer to major comment 3.

The figures and tables are clear, though the number of tables and figures within the manuscript could be reduced.

Removed: Figure 3, Table 6.

Supplement: Table 2, Figure 4, Table 3, Table 5

Citations are appropriate, however, it is unclear why the introduction focuses (e.g. Table 1) on wireless in situ *sensor systems, which are not really relevant, while previously published drifter studies from fluvial and oceanographic studies are not discussed in detail.*

We understand the comment, and have revised the introduction accordingly. The idea was to give a general overview of different available technologies to measure in the subglacial environments and then present drifters as additional possibility. We added additional references for fluvial and oceanographic drifter applications. And further clarified the introduction.

Major comments

1. With the exception of the "Moulin Explorer" and the eTracer, the introduction lacks a section describing what drifters are currently available (or have been used before). I believe that there are citations to drifters used in fluvial and oceanographic studies but no detail or discussion is present of their capabilities or performance. This is odd given the space afforded to wireless in situ sensors within glaciology, much of which isn't really relevant to this study. I would recommend that the introduction of Lagrangian drifters is expanded and that the removal of any strictly unnecessary sections is considered.

We removed unnecessary parts from the introduction and added information about fluvial and oceanographic drifters and their capabilities.

2. Given that this paper introduces a new instrument, the methods section lacks a decent description of the drifter electronics or the sensor's physical construction. The drifter's sensors are described but there is no description of the microprocessor used or the method of data storage. No schematic is provided and the method of fabrication is not mentioned.

The devices are made from more than 100 different electronic and mechanical components, a description of the complex fabrication process is therefore out of scope for this manuscript. A detailed technical overview of the drifter electronics is being prepared for the IEEE Sensors journal. We feel that a detailed overview of the electronics and communications, including schematics requires a stand-alone publication.

Hence, many questions present themselves such as how is the microprocessor programmed and in what language?

Information has been added as requested.

What is the sensor housing made from and how robust is it? Could it survive deployment in a subglacial channel?

We added additional information.

What water depth can the housing withstand? It would not be easy to replicate the experiment without further information and it is currently difficult to assess the limitations of the existing system.

These are practical questions which we overlooked, and appreciate the comment. Additional details have been added.

3. The description of the results is very verbose with many unnecessary explanations of standard statistical techniques and detailed descriptions of what is plotted in the figures. As such, the manuscript could be condensed with no loss of important detail. Please see specific comments below. Condensing the text may also highlight opportunities for minor restructuring (e.g. combining sections).

We cut down unnecessary explanations and condensed the result section. Several figures and tables have been removed or moved to the supplementary material.
The text has been condensed in the following:
Section 3.2, 3.3 and 3.4: Merged and condensed from 6 to 2 paragraphs.
Section 3.5 merged with 3.6: Condensed from 7 paragraphs to 3.
Section 3.7: Condensed from 2 paragraphs to 1.

Minor comments:

P2L8 – "has also been" rather than "was also"

Amended as suggested.

P2L9 - delete "the" before "channel"

Addressed.

P2L21 – given the intention to discuss new methods, SF6 tracing should be mentioned (e.g. Chandler et al. 2013). P2L25 - Andrews et al. (2014) also instrumented moulins and their results I would argue are more than encouraging. There are also a few other studies that are not cited so I suggest you use e.g. before the citations.

We have revised the references to include additional studies to provide a wider range of background material, with less focus on the subglacial environment.

P2L29 - while this is arguably true, it could also be argued that the majority of data still comes from wired sensors. There have also been recent developments in wired sensors. I'm not sure this needs mentioning and I would recommend focusing the introduction on drifters rather than borehole sensors.

We removed the part of the introduction in question and limited the discussion of borehole sensors to Table 1 of the supplementary material, as suggested we have focused specifically on drifters.

P2L34 – The sentence beginning "Drifters : : :" needs fragmenting, e.g. with commas. (Other sentences may benefit from this as well).

Changed following the reviewer's suggestion.

P3L16 - please state what you mean by "multimodal".

Stated as requested (P3, L11).

P3L29 – avoid the colloquial phrase 'already coming up'

Removed as suggested.

F1 caption – change "pressure holes" to "holes for pressure transducers"

Amended accordingly.

P7L3 - define POM

POM is now referred using the full name, Polyoxymethylene.

P7L7 - by total pressure do you mean what is normally referred to as gauge pressure, which is the pressure indicated by the gauge and not corrected for e.g. atmospheric pressure variability? What digital communications protocol do these sensors use? What resolution? Accuracy? More detail is required here.

We have added additional detail related to the total pressure sensor as requested (P4, L7-18).

P7L9 – 'linear calibration' rather than 'linearly rated'

Removed as suggested.

P7L12 - please explain what is meant by a second order corrective algorithm. Is this a second order polynomial? I realise this is described below but it could be clearer. If I follow right the zeroing is one-off so it's not right to say sub-diurnal variability I calibrated out as any post-zeroing variability in atmospheric pressure would not be corrected for.

Second-order refers to a two-stage process, and has been amended in the text accordingly by replacing "second order" with "two-stage". The algorithm first takes into account device-specific correction coefficients, specified by the manufacturer. In a second step, the device's temperature is used to output the corrected total pressure reading depending on the temperature range. The algorithm is provided by the manufacturer in their datasheet, page 7: https://www.te.com/global-en/product-CAT-BLPS0059.html

We added this information to the manuscript.

P8L10 - more discussion of the BNO055 calibration would be worthwhile. My understanding is that this sensor self-calibrates continuously, which I expect has advantages and disadvantages with implications for the data collected. Is changing this sensor one of the future technical improvements you allude to below?

We added additional information and provided references to the accuracy of the Bosch fusion algorithm.

P5L2 - write out month in full

Corrected as suggested.

P12L8 – typos: extra "an" and on L13 an extra "in".

Amended.

P12L21 - filtered how?

Additional information added (P10, L24-25).

P13L14 – This section could be condensed by assuming the reader understands basic statistics and with the use of symbols and terminology. See below.

The section has been shortened from three paragraphs down to one. Figure 4 and Table 3 were also removed and the section was merged with section 3.3. and 3.4. Section 3.2, section 3.3 and section 3.4 had 6 paragraphs in total and are now merged into two paragraphs.

P13L24 – 'assess' should be 'assesses', though 'identifies' or similar may be a better word here. That said skewness and kurtosis should not need defining, as they are standard statistical techniques.

We removed this from the text.

P13L25 – the terms ‘magnetometer in the y-direction’ and ‘gyroscope in the y-direction’ are somewhat awkward which makes it difficult to read. Perhaps use symbols instead? E.g. My, Gy. Euler angles are often referred to as yaw, pitch and roll and have standard symbols.

The terms have been amended accordingly and also included in figure 1.

P13L26 – “are slightly skewed towards values above the mean” can be written in less words as “are positively skewed”.

The text has been removed to improve clarity.

P13L30 – high kurtosis is referred to as ‘leptokurtic’. A kurtosis which is nearly Gaussian can be referred to as no kurtosis (or almost no kurtosis). This section can be condensed significantly if these terms are used.

This section has been removed.

P15L3 – delete ‘data set’ as its not necessary. The manuscript would be easier to read if unnecessary words were removed.

We removed unnecessary words from the manuscript.

P16L4 – you don’t need to explain Pearson’s correlation coefficient. Scientific papers would become impractically long if every standard technique was introduced. If a nonstandard technique is used by all means describe it in the methods (not the results). It’s also not necessary to list the classifications of Cohen et al. (1992) in full. Just say that you use their classifications in a single sentence and give the citation. If the reader is interested they can look it up. I would also recommend avoiding the style of describing what the figures show, as you do on L9-10. Instead I would recommend the style of making a statement or argument followed by the figure reference. This paragraph could be condensed to a few sentences without any loss of important detail. As it stands there are seven sentences before a result is described.

We shortened this and other paragraphs in the results section accordingly.

P18L5 and P23L3 and other occurrences – Phrases such as "the next plot in Figure 8" and "as shown in Figure 9" can be shortened by just giving the figure reference in brackets.

We amended the wording to shorten the text as suggested.

P23L2 and other occurrences – the first sentence here is methods and should not need repeating here.

We removed all sections, which described methods.

P25L5 – Referring to sample sizes on P14L9 you state that "These high numbers are however not necessarily an indicator of sensor accuracy, but rather an indicator of spatial and temporal flow variability", which obviously casts doubt on whether the calculations of a required sample size are useful at all. However, here you refer to the required sample size calculations again to conclude that such experiments will require "a significant number of deployments". Which of these is your preferred interpretation of your analysis on sample sizes?

We have clarified the interpretation on P14L9 as well as the discussion on P25L5.

P25L8 – Do you mean ($p > 0.05$) rather than less than?

Thank you for catching this error, it has been corrected.

P25L8/9 – how will technical improvements to the drifter reduce the number of deployments required? Please be specific. What are the specific issues with the drifter presented here? What needs to be improved?

Upgrades to the sensors to reduce the number of deployments are two-fold: First, the sensor electronics of the drifters will replace the BNO055 with a high-g accelerometer, as the current range is limited to +/- 16g and impact events can cause the accelerometer to become saturated. We believe the resulting data will improve the characterization of the signals, therefore reducing the number of deployments required. Second, the number of deployments can also be decreased with improved field deployment and recovery methods. Specifically, we are planning on reducing the size of the sensors to < 5cm maximal dimension, to reduce the chances of them getting stuck on deployment. We have added additional information in the discussion section.

Multi-modal sensing drifters as a tool for repeatable glacial hydrology flow path measurements

Andreas Alexander[1, 2], Maarja Kruusmaa[3, 4], Jeffrey A. Tuhtan[3], Andrew J. Hodson[2, 5], Thomas V. Schuler[1, 6], and Andreas Kääb[1]

[1]Department of Geosciences, University of Oslo, 0316 Oslo, Norway
[2]Department of Arctic Geology, The University Centre in Svalbard, 9171 Longyearbyen, Norway
[3]Centre for Biorobotics, Tallinn University of Technology, 12618 Tallinn, Estonia
[4]Centre for Autonomous Marine Operations and Systems, Norwegian University of Science and Technology, 7491 Trondheim, Norway
[5]Department of Environmental Sciences, Western Norway University of Applied Sciences, 6856 Sogndal, Norway
[6]Department of Arctic Geophysics, The University Centre in Svalbard, 9171 Longyearbyen, Norway

Correspondence: Andreas Alexander (andreas.alexander@geo.uio.no)

Abstract. Lagrangian drifters are a practical way to measure natural flow features in surface channels. In this study, small cylindrical drifters (length , diameter) were deployed in a supraglacial channel. Each drifter recorded the total water pressure, linear acceleration, magnetic field strength and rate of rotation at . Based on an ensemble analysis of repeated field deployments Glacial hydrology plays an important role in the control of glacier dynamics, sediment transport and of fjord and proglacial ecosystems. Surface meltwater drains through glaciers via supraglacial, englacial and subglacial systems. Due to challenging field conditions, the processes driving surface processes in glacial hydrology remain sparsely studied. Recently, sensing drifters have shown promise in river, coastal and oceanographic studies. However, practical experience with drifters in glacial hydrology remains limited. Before drifters can be used as general tools in glacial studies, it is necessary to quantify the variability of their measurements. To address this, we conducted field experiments in a 450 m long supraglacial channel with small cylindrical drifters equipped with pressure, magnetometer, acceleration and rotation rate sensors. The experiments (n = 55) , it was found in the supraglacial channel show that the pressure sensors consistently delivered yielded the most accurate data, where values remained within ±0.11 % of the total pressure time-averaged mean (95% confidence interval). Magnetometer readings also exhibited low variability across deployments, maintaining readings within ±2.45% of the time-averaged mean of the magnetometer magnitudemagnitudes. Linear acceleration measurements were found to have substantially larger 95confidence intervals, spanning a substantially higher variability of ±34.4% from of the time-averaged mean magnitudes. Furthermore, the drifter speed along the supraglacial channel was estimated by integrating the linear acceleration, providing a 95confidence interval of magnitude and the calculated speeds remained within ±24.5% of the time-averaged mean magnitude. The major contribution of this work is to provide a statistical assessment of multimodal drifters, repeatedly deployed in a long supraglacial channel reach, with a focus on developing a repeatable fieldmeasurement methodology including uncertainty. The results of this work along the flow path. Furthermore, our results indicate that prominent shapes in the sensor records are likely to be linked to variations in channel morphology and associated flow field. Our results show that multimodal drifters are capable of highly repeatable field measurements in can be a useful tool for field measurements inside supraglacial channels.

Future deployments of drifters into englacial and subglacial channels promise new opportunities for determining hydraulic and morphologic conditions from repeatable records of such inaccessible environements.

1 Introduction

Subglacial hydrology remains an important field of research due to its Glacial hydrology plays a key role in glacier dynamics (Flowers, 2018), sediment evacuation transport and its impact on fjord and proglacial ecosystems (e.g. Swift et al., 2005; Meire et al., 2017; Urbanski et al., 2017). The limited access to the subglacial environment complicates direct measurements and observations.Earlier works have acknowledged the role of subglacial water in glacier sliding (e.g. Weertman, 1972; Engelhardt and Kamb, 1 Surface water was found to control the basal motion of glaciers (e.g. Iken, 1972; Iken and Bindschadler, 1986; Hubbard and Nienow, 1997; as well as larger ice caps and ice sheets (e.g. Zwally et al., 2002; Van de Wal et al., 2008; Benn et al., 2009; Sundal et al., 2011; Stearns and Surface water is thereby able to enter the subglacial Surface water is generally routed supraglacially, i.e. along the glacier surface in ice-walled drainage systems. Water enters the englacial and subglacial drainage system through moulins, cracks, crevasses and cut-and-closure systems (Gulley et al., 2009). Ice-walled drainage systems have highly variable geometry, controlled by the counteracting mechanisms of melt enlargement due to dissipation of potential energy and creep-closure of the viscous ice (Röthlisberger, 1972). Therefore, the The capacity of the glacial drainage system adjusts to variable supply by melt water from the surface (Schoof, 2010; Bartholomew et al., 2012) . Step-pool sequences are formed as a series of geometric adjustments (e.g. Vatne and Irvine-Fynn, 2016) and represent varies in both space and time and dynamically adjusts to the highly variable meltwater supply (Schoof, 2010; Bartholomew et al., 2012) . These geometric adjustments often form step-pool sequences (e.g. Vatne and Irvine-Fynn, 2016) and are responsible for up to 90% of the total flow resistance of a stream (Curran and Wohl, 2003) , leading to an important role of channel pattern and morphology on (Curran and Wohl, 2003) . The channel geometry influences flow resistance and water velocity (Germain and Moorman, 2016). Water velocity was also shown to control Vice versa, the velocity controls the incision rates in ice-walled channels in conjunction with water temperature and the rate of heat loss at the channel boundaries (Lock, 1990; Isenko et al., 2005; Jarosch and Gudmundsson, 2012). Despite these advancesfindings, major knowledge gaps remain. Largely unknown are the mechanisms behind how water is routed , especially within subglacial hydrology due to limited observations of the environment. Specifically, the mechanisms driving water routing from the glacier surface to the bed . The role of subglacial water remain largely unexplored. Improving our understanding of glacial hydrology and its effect on glacier dynamics therefore requires new methodsfor the . The methods should be able to provide direct measurements of the subglacial environment water routing on, through and under glaciers including the water temperature, the velocities velocity, pressure as well as the pressures and the flow path channel morphology along multiple flow paths.

However useful, direct measurements are scarce and Direct measurements are the most ideal source of information, but remain scarce in glacial hydrology because they are difficult to obtain . This is largely due to the limited accessibility of the subglacial environment which is governed by high pressures (Iken and Bindschadler, 1986; Rada and Schoof, 2018) , high sedimentation rates (Walder and Fowler, 1994) , abrasion (Haldorsen, 1981) and turbulent water flow (Kor et al., 1991) . (e.g. Gleason et al., 2016) . Beginning in the early 2000s, new technologies have emerged(presented in more detail in Table ??), which open new, promising pathways towards an improved understanding of subglacial hydrology (e.g. Martinez et al., 2004; Hart et al., 20 and are outlined in Table A1 of the supplementary material. Current methods for in-situ tests include Doppler current profiling in supraglacial systems (e.g. Gleason et al., 2016) , dye tracing (e.g. Seaberg et al., 1988; Willis et al., 1990; Fountain, 1993; Nienow et al., 1998; Hasnain et al., 2001; Schuler and Fischer, 2009), salt injection gauging (e.g. Willis et al., 2012), geophysical methods (e.g. Diez et al., 2019) , and direct observations are available from borehole instrumentation (e.g. Iken and Bindschadler, 1986; There are also encouraging attempts to deploy sensors in moulins (Iken, 1972; Vieli et al., 2004) . Direct access of the glacier base has been exploited to collect measurements at the subglacial laboratory in Engabreen, Norway (e.g. Cohen et al., 2006; Iverson et al., 2 well as at the Argentière glacier in the French Alps (e.g. Vivian and Bocquet, 1973; Goodman et al., 1979; Hantz and Lliboutry, 1983) . and gas tracing (e.g. Chandler et al., 2013) .

Most of the recent developments in sensors in glacial hydrology (see Table ?? for a detailed overview) have been focused on devices which can perform borehole measurements which can be transferred wirelessly through the ice (e.g. Martinez et al., 2004; Hart et al. The major limitations of fixed-position observations is that they have to be deployed via borehole, decreasing the chances to enter a subglacial system, and that boring requires a high deployment cost. This has motivated the development of Lagrangian sensors which move with the changing environment, thus providing a wider range of observational data at a substantially lower deployment cost. Drifters are small Lagrangian drifters are small floating devices which passively follow the water flow and are commonly used in large-scale surface flow studies and are able to to study flow in large rivers, lakes and oceans. Most typically, drifters provide information about their position and speed (Landon et al., 2014). Depending on their sensor payload, drifters can be used for a wide range of applications, including coastal and ocean surface current monitoring (Boydstun et al., 2015; Jaffe et al., 2017), to estimate river bathymetry and surface velocities (Landon et al., 2014; Almeida et al., 2017) and to collect imagery for underwater photogrammetry (Boydstun et al., 2015). Recent payloads in river studies included sensors for temperature (e.g. Tinka et al., 2013; Oroza et al., 2013; Allegretti, 2014) , dissolved oxygen (e.g. D'Este et al., 2012; Tinka et al., 2013) , pH (e.g. Tinka et al., 2013; Arai et al., 2014) , turbidity (e.g. Marchant et al., 2015) , as well as GPS receivers (e.g. Stockdale et al., 2008; Tinka et al., 2013) , Acoustic Doppler Current profilers (e.g. Tinka et al., 2009; Postac Inertial Measurement Units (e.g. Arai et al., 2014) . Additionally, sensor payloads in oceanographic applications included devices for the measurement of conductivity (e.g. Reverdin et al., 2010; Jaffe et al., 2017) , chlorophyll (e.g. Jaffe et al., 2017) and underwater imagery (e.g. Boydstun et al., 2015; Xanthidis et al., 2016) . Drifters remain the most promising method for the study of physical parameters along multiple flow paths within the hydrological system of a glacier. This is because Lagrangian drifters can be equipped with multiple sensors to collect data along the flow path within the changing environment. Therefore they provide a wider range of observational data with reduced deployment effort when compared to conventional fixed station hydrological measurements.

~~The use~~ Development of sensing drifters in glaciology has been previously reported, most notably the Moulin Explorer by Behar et al. (2009) ~~,~~ which was unfortunately lost during its first deployment~~, and the development was afterwards discontinued~~. A successful glacial drifter was the E-tracer, as reported by Bagshaw et al. (2012). The device ~~was~~ has the size of a table tennis ball and included a radio transmitter ~~capable of transmitting~~ to enable identification and data transmission after passage through the subglacial ~~environment on the margin~~ system of Leverett Glacier~~in Greenland, reemerging at the glacier portal .~~, Greenland (Bagshaw et al., 2012). These encouraging results lead to a second generation of E-tracers equipped with a pressure sensor, and successfully transmitted pressure data from subglacial channels through 100 meters of overlying ice after having been deployed in crevasses and moulins (Bagshaw et al., 2014). The published data remains however sparse and limited to a single mean pressure ~~plot~~ record in Bagshaw et al. (2014). As with all new field measurement technologies, the repeatability of in-situ measurements is often very challenging to determine. Encouraged by the previous drifter studies ~~from~~ by Bagshaw et al. (2012) and Bagshaw et al. (2014) with a single pressure sensor, the present study explores the potential of ~~multi-modal sensing drifters to extract~~ sensing drifters with several different sensors (multi-modal) to record data along the flow path of glacier channels. The focus of this work is to assess the repeatability of Lagrangian drifter ~~measurement data, with a specific focus on glacial hydrology~~measurements in a supraglacial channel. Current methods, such as dye tracing, allow for the repeatable measurement of the flow velocities averaged over the duration of a passage. However, it is impossible to deconvolve these records to obtain spatially and temporally distributed information. The present study therefore also assesses the potential of sensing drifters to acquire spatial and temporal variation of the velocity along a flow path. Furthermore, the multi-modal sensor data are investigated for potential time series features that may be associated with geometrical features of the investigated supraglacial channel. ~~The experiments are achieved by~~

The experiments were carried out using a submersible multi-modal drifter platform measuring at 100 Hz. The ~~small, low-cost (500 EUR) platform records total water pressures,~~ rugged, autonomous sensing platform records the water pressure, and three components each of linear acceleration, rotation ~~rates~~ rate and the magnetic field strength~~via repeated deployments along~~ . Repeated deployments were carried out along a single section of a ~~section of~~ supraglacial meltwater channel (n = 55). The general applicability of the ~~multi-modal~~ cylindrical drifter is field-tested, and the repeatability of ~~each of~~ the sensor time series is determined. Finally, we investigate the potential of the proposed multi-modal drifter to measure the surface transport velocity along a supraglacial channel flow path, and critically assess the device's performance for glaciological applications. ~~As the sensing drifters used here are for the first time employed in a glacial environment, our study aims at characterizing sensor performance and suitability, rather than already coming up with detailed glaciological data interpretations~~The deployment in supraglacial channels allowed the study of the sensor performance in a controlled environment. This is an important step in the development of a reliable measurement platform for supraglacial, englacial and subglacial studies.

~~X X X X X X X X Overview of subsurface glaciology sensing platforms reported in the literature. Paper Measured parameters Deployment Communi- cation Lifetime Published data? Study purpose Additional information~~

~~Martinez et al. (2004) Orientation, pressure, temperature Borehole Wireless, Short-term Yes Development of sensor network Glacsweb project~~

Hart et al. (2006) Pressure, tilt angle, temperature, resistivity, strain gauge Borehole Wireless One year Yes Clast transport Installed in sediment, Glacsweb project

Behar et al. (2009) Pressure, temperature, 3D acceleration Moulin Iridium Short-term No Conference Abstract/ Sensor development Platform lost during deployment

Rose et al. (2009) Temperature, pressure, resistance, tilt Borehole Wireless, One year Yes Basal conditions Glacsweb project

Hart et al. (2011a) Temperature, water pressure, probe deformation, conductivity, tilt Borehole Wireless, One year Yes Till behaviour Glacsweb project

Hart et al. (2011b) Water pressure, probe deformation, conductivity, temperature Borehole Wireless, 1-2 years Yes Investigation of glacier break-up Glacsweb project

Bagshaw et al. (2012) Radio beacon, pressure Moulin Wireless, Short-term Yes Drifter development Only feasibility test of drifters, stationary pressure recordings

Smeets et al. (2012) Water pressure Borehole Wireless, 10 years Yes Subglacial pressure Wireless transfer through up to ice thickness

Lishman et al. (2013) Acoustic attenuation Borehole Wireless, different frequencies Short-term Yes Acoustic communication through ice predicted to be most feasible frequency for communication

Bagshaw et al. (2014) Pressure Moulin Wireless, / Short-term Yes Development of drifters Stationary Cryoegg Bagshaw et al. (2014) Pre temperature, conductivity Moulin Wireless, / Short-term Yes Development of driftersETracer drifter

Hart et al. (2015) Temperature, water pressure, probe Borehole Wireless, One year Yes Study subglacial/ englacial waterflow Glacsweb project

van de Wal et al. (2015) Pressure Borehole Wireless, One year Yes Ice velocities Platform from Smeets et al., 2012

How et al. (2017) Pressure, temperature, tilt Borehole Wireless, 7-14 months Yes Subglacial hydrology Platform from Smeets et al., 2012

Martinez et al. (2017) Passive seismics, 3D acceleration, digital compass, temperature Borehole Cabled/ Wireless, Short-term deployment Yes Glacier stick-slip Fixed location Geophones, Glacsweb project

Bagshaw et al. (2018) Pressure, conductivity, temperature Borehole Wireless, 3 months Yes Subsurface firn/ snow studies Merged Cryoegg and ETracer platform

Hart et al. (2019) Pressure, stress, conductivity, tilt, temperature Borehole Wireless, Up to 2 years Yes Glacier stick-slip motion, till deformation Glacsweb project This study Pressure, acceleration, magnetic field, spinning rate, Euler angels Moulins, meltwater channels WiFi, after recovery Short-term Yes Drifter proof-of-concept and data repeatability assessment Reliability study, time series feature detection

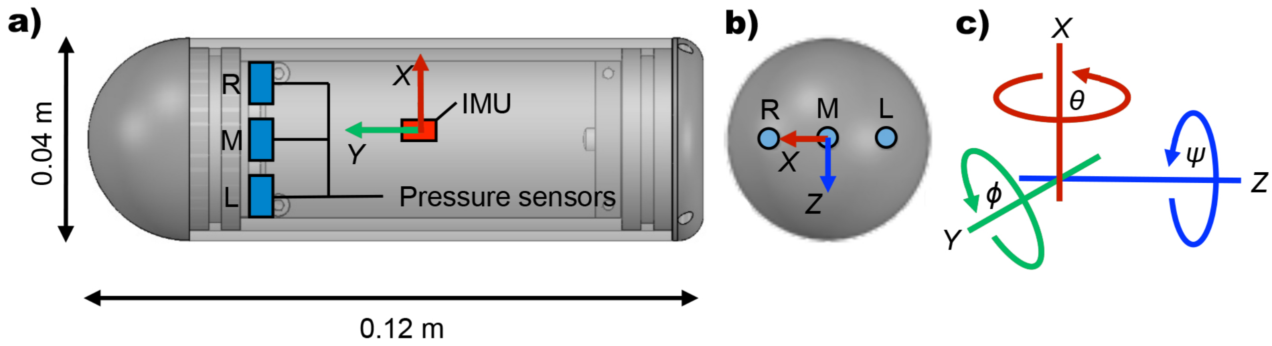

Figure 1. ~~Schematic and dimensions~~ Dimensions of the multi-modal drifter used in this work~~showing the locations of the~~. The drifter includes three identical pressure transducers ~~and the~~ as well as a single inertial measurement unit (IMU). ~~Left~~a): Side-view of the drifter. ~~Middle~~b): Top-view facing the cap showing the left (L), middle (M) and right (R) ~~pressure~~ holes pressure ports. ~~Right~~c): ~~Drifters on~~ Body-oriented drifter coordinate system including the ~~glacier surface shown with attached balloons used for manual buoyancy adjustment~~roll (ϕ), pitch (θ) and yaw (ψ) angles.

2 Methods

2.1 Multi-modal drifter

The drifter platform used in this study has ~~a housing consisting of two POM~~ two custom machined Polyoxymethylene (POM) plastic end caps and a 4 cm outer diameter polycarbonate plastic tube~~, with~~. The device has a total length of 12 cm, and mass of 143 g. Neutral buoyancy of the drifter is achieved by manually adjusting the length of the sensor by screwing the flat end cap inwards or outwards to ~~modify~~ increase or decrease the total volume. ~~Balloons~~ Small balloons can additionally be attached to the drifter, to ~~further adjust the buoyancy , as seen in the right panel of Figure 1. Balloons are~~ fine tune the buoyancy in the field and were used during the field deployment of this study. Each hemispherical end cap of the drifters contains three identical digital total pressure transducers. ~~The~~ When the device is submerged in flowing water, the total pressure is the sum of the atmospheric, hydrostatic and hydrodynamic pressures. The devices are designed for a maximum pressure of 2 bar ~~span transducer~~ (MS5837-2BA, TE Connectivity, Switzerland) ~~are programmed with~~ and a sensitivity of ~~(~~0.02 mbar (0.2 mm water column). ~~They are linearly rated for of water depth, and can be used up to of water depth using a non-linear correction based on laboratory calibration.~~ The pressure sensor data were recorded with a resolution of 0.01 mbar. The accuracy of the pressure transducers was found to be 1 mbar. This was determined by testing fully assembled drifters in a laboratory barochamber up to an equivalent of 55 m of water depth, which is 2.75 times larger than the maximum rated pressure of the sensor. Therefore, the main limitation of the drifter platform results from the measurement range of the chosen pressure sensors, rather than the ability of the mechanical components. Each pressure transducer is equipped with its own on-chip temperature sensor, allowing for all pressure readings to include real-time temperature correction using a ~~2nd order~~ two-stage correction algorithm. The algorithm first takes into account device-specific correction coefficients, specified by the manufacturer. In a second step, the device's temperature is used to output the corrected total pressure reading depending on the temperature range. The algorithm is provided on page 7 of the manufacturer's data sheet (TE connectivity sensors, 2017) .

All ~~drifter units are equipped with an~~ drifters are programmed for atmospheric auto-calibration~~algorithm~~. Once the ~~devices have been~~ device is activated using a magnetic switch, data from each pressure transducer is logged for ~~15 seconds~~15 s. The atmospheric pressure, including ~~the~~ any sensor-specific offset, is recorded internally. Afterwards, all three transducers are set to a default value of 100 kPa at local atmosphere. All sensors are therefore auto-calibrated to local changes in atmospheric pressure ~~,~~ which occur during the day, directly before each field deployment. This feature removes the necessity of manually correcting pressure sensor readings in post-processing. The drifter units use three pressure sensors (marked as Left, Middle and Right in Figure 1), and can be outfitted with either 2 bar or 30 bar sensors~~, as opposed to a single pressure sensor providing~~ . The drifters were designed this way to include triple modular redundancy by including a pressure sensor array in lieu of a single pressure sensor. The middle pressure sensor (30 bar sensor) was however not used in this study due to the lower sensitivity and range of pressures experienced during channel passage. All following work will therefore only refer to the two lateral (left and right, 2 bar) pressure sensors.

In addition to the three pressure transducers, the drifter platform also contains a digital 9 degree of freedom (DOF) inertial measurement unit (IMU) (BNO055, Bosch Sensortec, Germany) integrating linear accelerometer, gyroscope and magnetometer sensors. The device uses proprietary (Bosch Sensortec) sensor fusion algorithms to combine the linear accelerometer, gyroscope and magnetometer readings into the body-oriented Euler angles to provide real-time absolute orientation at 100 Hz. These IMU sensors were chosen as they represent the current state-of-the-art in IMU technology. Additionally, they have the further benefit that the real-time calibration status of each of the three sensors is recorded (0, lowest to 3, highest) as part of each data set in order to provide quality control information for all IMU measurement data. When running in sensor fusion mode, all variables are saved at 100 Hz, with the exception of the magnetometer, which is recorded at a maximum rate of 20 Hz. ~~Vibration and destructive testing of the IMU have additionally been conducted up to 3000 times the gravitational acceleration, thus showing that the drifter platform is suitable for deployment under harsh conditions.~~ The sensor fusion mode of the BNO055 has the major benefit that the absolute orientation, consisting of roll, pitch and yaw angles, is calculated in real-time. The major downside is however that the calibration and sensor fusion used in this procedure are a "black box", as Bosch has not released the algorithms. Previous studies in highly dynamics environments report the measurement error of the BNO055 in the pitch and yaw angles for rapid body movements during driving as less than 0.4° and less than 2° for the roll angle (Zhao et al., 2017) . Similar results were observed for a series of static and dynamic tests using a hexahedron turntable with the BNO055, where the error ranged from 0.53° to 0.86° for pitch angles, 1.28° to 3.53° for yaw angles, and 0.44° to 1.41° for the roll angle (Lin et al., 2017) .

Table 1. Overview of the drifter text file data format. Each of the 27 columns corresponds to a different variable saved during channel passage at 100 Hz (magnetometer 20 Hz), units given in parentheses.

Col 1	Col 2	Col 3	Col 4	Col 5	Col 6	Col 7	Col 8	Col 9
Timestamp (ms)	Pressure left (hPa)	Left temp (°C)	Pressure center (hPa)	Center temp (°C)	Pressure right (hPa)	Right temp (°C)	Euler angle ~~X~~ θ (deg)	Euler angle ~~Y~~ ϕ (deg)
Col 10	Col 11	Col 12	Col 13	Col 14	Col 15	Col 16	Col 17	Col 18
Euler angle ~~Z~~ ψ (deg)	Quat. X (-)	Quat. Y (-)	Quat. Z (-)	Quat. W (-)	Magnet. X (μT)	Magnet. Y (μT)	Magnet. Z (μT)	Dynamic linear accel. X ($\mathrm{m\,s^{-2}}$)
Col 19	Col 20	Col 21	Col 22	Col 23	Col 24	Col 25	Col 26	Col 27
Dynamic linear accel. Y ($\mathrm{m\,s^{-2}}$)	Dynamic linear accel. Z ($\mathrm{m\,s^{-2}}$)	Rate gyro X ($\mathrm{rad\,s^{-1}}$)	Rate gyro Y ($\mathrm{rad\,s^{-1}}$)	Rate gyro Z ($\mathrm{rad\,s^{-1}}$)	Calibration status magnet. (0-3)	Calibration status accel. (0-3)	Calibration status gyro. (0-3)	Sum calibration status (0-9)

The drifters use the STM32L496 microcontroller unit (MCU). They are programmed with the STM32CubeMX software in DFU mode over a USB full speed interface. A ESP8266 WiFi module is used for communication and connected to the MCU via USART2. The IMU and pressure sensors are connected via an I^2C interface and communicate via the I^2C protocol. The data is stored as a delimited text file at 100 or 250 Hz directly to a 6 or 16 GB microSD card. The IMUs were configured to read out more data in addition to the dynamic linear acceleration (body acceleration due to external forcing only, gravity vector removed) and rate of angular rotation (rate gyro), relative to the x-, y- and z-axes of the sensor, as shown in Figure 1. The additional data include the real-time calculation of the drifter body-orientation (3D Euler angles relative to x-, y-, and z-axes and the angles as Quaternions) as well as the 3D magnetic field vector. The orientation of the vector measurements of the magnetometer readings correspond to the axes of the sensor which are identical to the accelerometer and rate gyro axes. All drifter sensor data is saved as a 27 column ASCII text file with the structure listed in Table 1. The text files were transferred from the drifters via Wifi to a field computer after drifter recovery from the stream.

Vibration and destructive testing of the IMU and the drifter housing have been conducted up to 3000 times the gravitational acceleration, thus showing that the drifter platform can withstand high impacts. Deployment under harsh conditions was successfully proven during measurements inside large-scale hydropower turbines (Kriewitz-Byun et al., 2018) . During this study the drifter was only tested in supraglacial streams. Subglacial deployments have however been successfully conducted during subsequent field tests in 2019 and will be described and analysed in a later study.

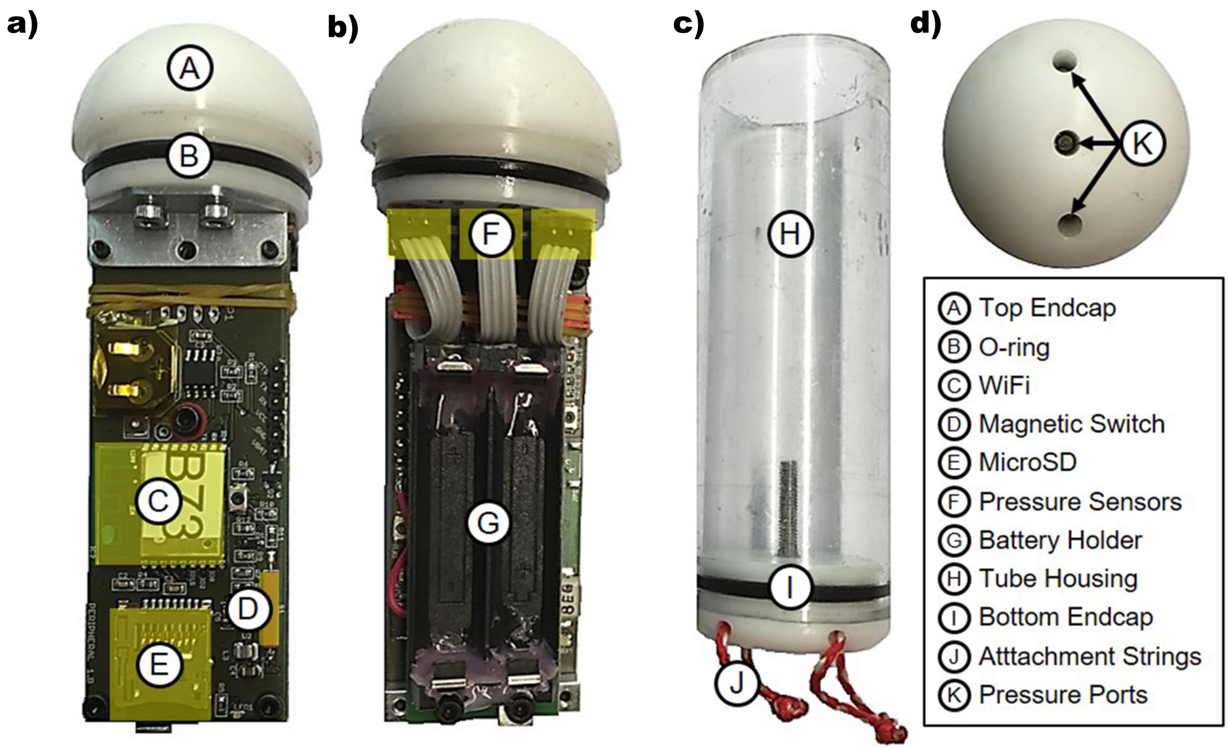

Figure 2. Detailed breakdown of the drifter. a): Side-view showing the drifter electronics. b) Side-view showing the reverse side of the electronics board including the battery holder and pressure sensors. c) Polycarbonate tube housing of the drifters with attachment strings for balloons used for manual buoyancy adjustment. d) Top-view facing the cap, showing the ports for each of the three pressure sensors.

2.2 Study site

Fieldwork for this study was conducted between 04.08 and 07.08.2018 on the small valley glacier Foxfonna, located on the on the main island of the Norwegian Arctic archipelago Svalbard between the 4th and the 7th of August, 2018 on the approximately 5 km^2 big valley glacier Foxfonna. The cold-based, roughly 2.9 kilometers long glacier is located on a northwest-facing slope between 330 and 750 meters elevation above sea level at the end of the Adventdalen valley, next to the main settlement at Longyearbyen. The glacier has a network of supraglacial channels developing on the surface of the glacier during summer timethe summer ablation period. Some of the channels either cut deep enough to form englacial cut-and-closure systems (Gulley et al., 2009) or they are still partly and others remain partially snow-plugged during summer timethe summer. Additional channels emerge at the glacier front, indicating existing subglacial drainage channels.

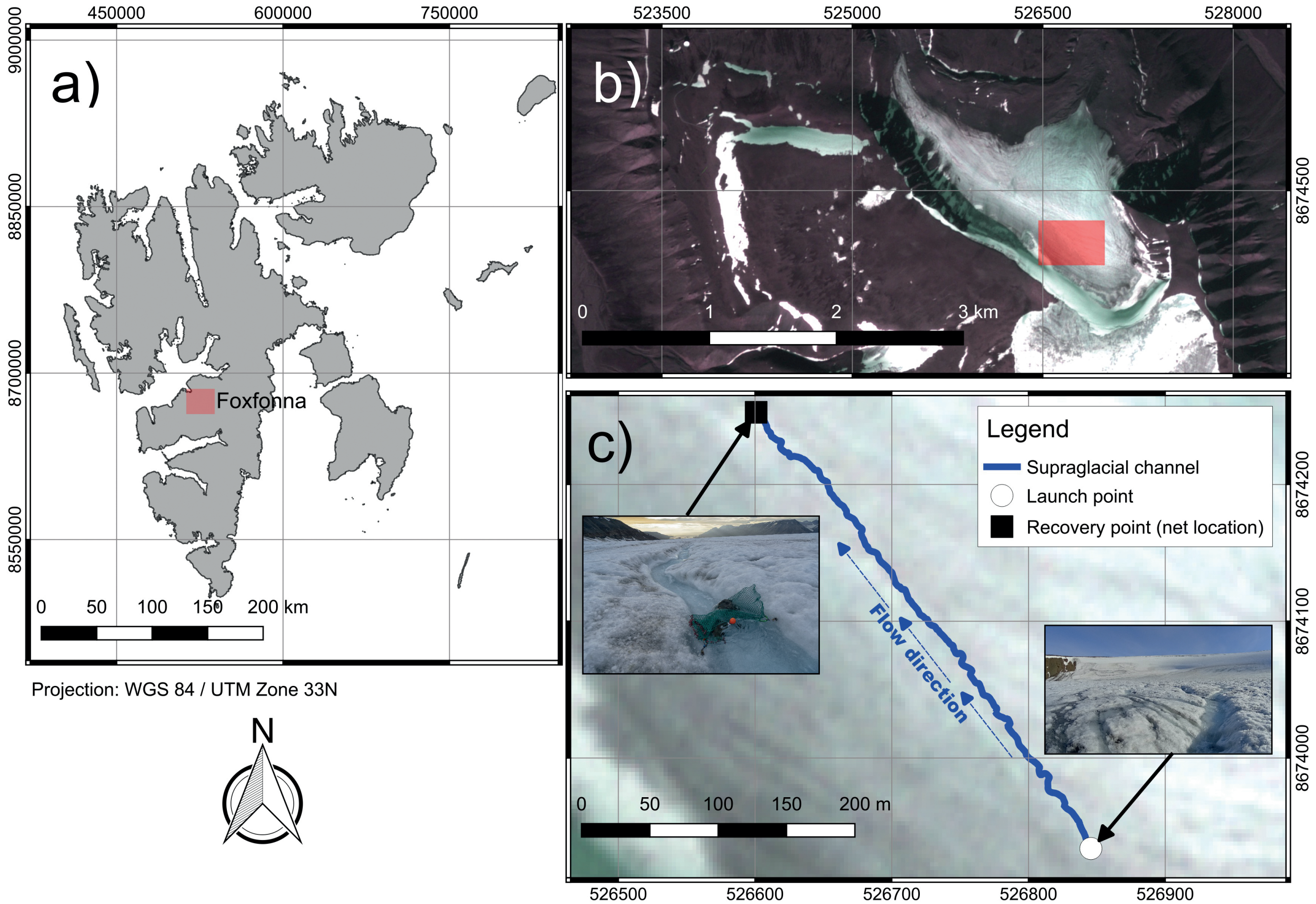

Figure 3. a) Location of the Foxfonna glacier on the Svalbard archipelago. ~~Basemap: © Norwegian Polar Institute.~~ b) PlanetScope false color overview of the Foxfonna glacier and the location of the investigated supraglacial channel acquired on 01.08.2018. c) Close up of the studied supraglacial channel. Background image from PlanetScope acquired on 01.08.2018.

2.3 Field Deployments

Two different experiments were conducted on the glacier surface. The first experiment tested the general feasibility of the drifters ~~to travel~~ traveling through an englacial/subglacial system and ~~to be successfully recovered. The first experiment~~ being recovered. This involved deploying five wooden drifter surrogates identical in size to our multi-modal drifters in a 2.5 km long supraglacial, partly englacial channel. The channel on the eastern side of the glacier had several well-developed step-pool sequences and was incised deeply into the glacial ice. Further downstream, the channel developed into a ~~partly~~ partially snow-plugged, ~~partly~~ partially englacial system. The final channel section had a ~~high~~ large amount of debris ~~, representative~~ typical of subglacial environments. A net was installed where the channel reemerged on the surface at the eastern lateral moraine.

Reemerging ~~dummies~~ wooden sensor surrogates were trapped in the net and recovered by removing them by hand.

The second, main experiment was conducted along a 450 m section of a ~~Foxfonna supraglacial channel . The investigation~~ supraglacial channel on Foxfonna. The investigated section had a total elevation difference of ~~30 meters~~ 30 m (handheld GPS accuracy of ~~5 meters~~5 m) as measured between the start and the end of the channel section. The section included several step-pool sequences as well as rapids and recirculation zones. The experiments were conducted within this channel section for three ~~principle~~ main reasons. First, the purpose of the study was to determine field measurement repeatability, requiring a channel with different morphological features. Second, with only five prototypes, the risk of losing a drifter had to be kept low. Finally, the study of the supraglacial system allowed for the filming of deployments, and this provides a simple and robust evaluation method to compare the sensor data with observed movements of the drifter within the flow. All five drifters were launched from the ~~green marked location~~location, marked with a white circle on the map in Figure 3, and were recovered using a marine fishing net, installed at the downstream end of the channel section. A total of 55 drifter deployments with five individual multi-modal drifters were conducted. 10 deployments were collected in the afternoon of the second field day (05.08.2019 15:52 -17:20 local time) and the remaining 45 deployments in the late evening and night of the fourth field day (07.08.2019 18:53 – 23:37 local time). ~~It must be stated that the~~ The discharge varied throughout the deployment time, depending largely on weather conditions (sunny, with increased melt on 05.08 and cloudy, rainy, and sunny on 07.08). The exact discharge was not recorded. Some of the deployments had slightly varying buoyancy, due to varying balloon inflation, but all deployments on the 450 m section were conducted with a single balloon. Four out of the ~~fifty-five~~ 55 deployments had the drifters connected in tandem with cable ties, to test the variation between the sensor readings of two different drifters passing through nearly identical flow paths. All of the drifters were switched on and then left on the ground for at least ~~30 seconds~~ 30 s before deployment and for an additional ~~30 seconds~~ 30 s after successful recovery from the stream and before switching off. This was done to ensure that the drifters had enough time for self-calibration to atmospheric pressure before the deployment and the IMU sensor readings could calibrate and provide constant-value readings, which later serve to mark the start and stop of each deployment.

2.4 Data preparation and processing workflow

~~Overview over the multi-modal drifter data post-processing workflow.~~

All data processing was performed using Matlab R2018b. Corrupted datasets with missing data or faulty sensor readings were removed (n=9). In cases where a drifter switched off and back on again during a deployment, multiple files were concatenated into a single dataset. The start and end of each dataset were manually trimmed such that ~~that~~ the processed time series only represent the time within the glacial stream. Threshold criteria used, for determining the start of measurement, were the linear acceleration peaks of a drifter's first impact with the water surface during deployment as well as the final impact when the drifter contacted the net during recovery. ~~Lines~~ Entries in the dataset with no data or poor calibration status were filtered out in the next step. After trimming, the time series data were filtered for outliers with the following thresholds: ±200 µT for the magnetometer, $\pm 60\,\mathrm{m\,s^{-2}}$ for the linear accelerometer and $\pm 50\,\mathrm{deg\,s^{-1}}$ for the rate gyro.

The statistical analysis evaluated the degree of agreement between individual sensor time series for each deployment to assess the repeatability of the drifter field data. Pearson product-moment correlation coefficients were used to investigate the correlation structure between different sensor modalities, and to assess if the different modalities were dependent or independent variables. The associations were classified with a modified scheme from Cohen (1992) . In the next step, the empirical probability distributions were investigated together with the statistical moments mean, variance, standard deviation, skewness and kurtosis. Afterwards, the empirical probability distributions of each deployment were compared to the ensemble empirical probability distributions to determine the measurement repeatability. To ensure a robust assessment of repeatability, several criteria were evaluated: chi square distances, mean absolute error, mean squared error, data ranged normalized root mean square and the Kullback Leibler divergence (Kullback and Leibler, 1951).

The assessment of the minimum needed sample size to achieve a given precision of each mode (e.g. total pressure, linear acceleration in the x – direction) was done following the equation from Hou et al. (2018)

$$n = \frac{Z^2_{1-\frac{\alpha}{2}}}{\varepsilon^2} \cdot \left(\frac{\sigma}{\mu}\right)^2 \tag{1}$$

where $Z^2_{1-\frac{\alpha}{2}}$ is the standard normal deviate (e.g. $Z_{0.975} = 1.96$ for the 95% confidence interval), ε is the defined precision, σ is the standard deviation of the population and μ is the population mean. In this study, we ~~defined the~~ set the desired error of the sample mean to be within ±10% of the true value (i.e. $\varepsilon = 0.10$), 95% of the time (i.e. $Z_{0.975} = 1.96$). The values for σ and μ were then obtained from the statistical analysis of the time series data from all deployments.

To find potential features in the time-series and to test ~~if the recorded data is varying~~ the degree to which data vary over time, moving means were calculated over the dataset. The moving means for this study were calculated over a time window of ~~five seconds~~5 s, as potential signal features were most prominent at this window length, and plotted together with the 95% confidence interval (CI). This was done for ~~forty~~ 40 of the deployments ~~(n=40)~~ for the first ~~200 seconds~~ 200 s of the channel passage. The analysis was limited to the first ~~200 seconds~~200 s, as not all drifters recorded for the full length of time, so that a compromise had to be found between ~~getting as many deployment datasets as possible with an as long time span possible at the same time~~maximizing the total number of deployments as well as the total duration of deployment. The other 15 deployments out of the total 55 deployments were left out as they either recorded no data (n=9) or recorded only for parts of the passage (n=6) leading to very short datasets.

The surface transport speed was calculated by integrating the acceleration measurements over a rolling time window for the remaining 40 deployments (n=40). The window width was ~~in an initial step~~ initially randomly chosen for the velocity calculation. Once the three components of the velocity vector were calculated, we defined the transport speed as the magnitude of the velocity. The transport speed was then compared to the estimated transport velocity, which was found by dividing the transport distance (450 m) by the total travel time of the drifter. The integration window size was then readjusted individually for every deployment, so that it would be within a 10% error threshold from the drifter's estimated transport velocity. By doing so, the individual changes in the observed transport velocity are accounted for. As the acceleration includes rapid changes in rigid body motion, for instance due to impact with the channel walls, we found that integration produced large outliers, which are not representative of the water flow itself. Therefore the estimated instantaneous velocities, ~~whose absolute values exceeded~~ exceeding $10\,\mathrm{m\,s^{-1}}$, were ~~filtered~~removed.

3 Results

3.1 Utility rate

In the first experiment, five wooden dummies, of the same size and buoyancy as the drifter, were deployed in a 2.5 km long supraglacial, partly englacial channel with features of subglacial channels ~~, and~~ (step-pool, glide and chute sequences and debris at the channel bootom) , and four out of five dummies were recovered after 72 hours. The second experiment consisted of 55 multi-modal drifter deployments in a 450 m supgraglacial channel section, returning a total of 40 useful datasets. The other 15 deployments had ~~either too short datasets (below 200 seconds~~datasets of insufficient duration (below 200 s, compared to an average transit time of ~~360 seconds~~360 s), as drifters only recorded part of the deployments there (n=6) or recorded no data at all ~~. This leads~~ (n=9). This lead to the definition of a recovery and a utility rate for the drifter deployments:

$$\text{Recovery rate} = \frac{\text{Number of recovered dummies/ drifters}}{\text{Number of deployed dummies /drifters}} \tag{2}$$

$$\text{Utility rate} = \text{Recovery rate} \cdot \text{Data usability rate} = \frac{\text{Number of recovered dummies/ drifters}}{\text{Number of deployed dummies/ drifters}} \cdot \frac{\text{Number of usable datasets}}{\text{Number of recovered drifters}} \tag{3}$$

$$\text{Utility rate} = \text{Recovery rate} \cdot \text{Data usability rate} \tag{4}$$

Supraglacial system from the second experiment with 5 drifters and a total of 55 deployments in 450 m long supraglacial channel:

$\text{Recovery rate} = \frac{55}{55} = 1.00$ ~~,~~

$\text{Utility rate} = \frac{55}{55} \cdot \frac{40}{55} = 0.73$ ~~.~~

Subglacial/englacial system, based on the assumption that the drifters can pass through the system, if the dummies pass through. The results from the first experiment with 5 dummies in the 2.5 km long channel is used:

$\text{Recovery rate} = \frac{4}{5} = 0.80$ ~~,~~

Estimated total utility rate for **subglacial/englacial** deployments based on dummy deployment and data usability rate:

Utility rate $= \frac{4}{5} \cdot \frac{40}{55} = 0.58$.

3.2 ~~Empirical probability density distributions~~Statistical evaluation

~~Empirical probability distributions of 40 deployments (n=40) of the recorded sensor data in blue with a normal fit in red.~~

~~Ensemble statistics of all multi-modal time series: mean, variance, standard deviation, skewness and kurtosis. Sensor mode mean variance standard deviation skewness kurtosis Pressure left Pressure right Magnetometer X Magnetometer Y Magnetometer Z ||Magnetometer|| Accelerometer X Accelerometer Y Accelerometer Z ||Accelerometer|| Gyroscope X Gyroscope Y Gyroscope Z ||Gyroscope|| Quaternion X Quaternion Y Quaternion Z Quaternion W Euler X Euler Y Euler Z~~

~~Empirical probability density distributions in combination with ensemble statistics allow a simple overview of each dataset, the distribution of a parameter's values and their variability. Figure ?? shows the empirical probability density distributions of~~ We calculated the ensemble statistics for all successful deployments~~(n=40) and all sensor records as well as the IMU calculations for Quaternions and Euler angles. Additionally, the normal distribution fitted to each dataset is plotted as a red line. Both the visual interpretation of the empirical probability distributions in Figure 4 as well as the mean values in Table ?? strongly indicate that the values for the acceleration, rate gyroscope and the quaternions are close to zero, meaning the drifters remained nearly motionless for long periods of time during measurement. This is due to many of the drifters being stuck in the channel for several minutes before they were dislodged and carried further by the current.~~

~~The skewness of the distributions indicates the asymmetry of the data around the origin. It therefore assess whether a dataset is symmetric or if it is deviating from a central tendency. The pressures, magnetometer in the y-direction, gyroscope in the x-direction and the Euler angles in both the x- and y-directions are slightly skewed towards values above the mean. The acceleration in the y-direction is more skewed towards positive values due to the orientation (facing down and into the direction of motion) of the drifter as it was advected by the flow. All other sensor readings are more skewed in the negative direction from the mean.~~

~~A kurtosis of value 3 indicates distribution similarity to a Gaussian distribution. The left pressure sensor readings, magnetometer in x-direction and the Euler angles in the y- and z-directions exhibit a kurtosis, which is nearly Gaussian. All other sensor readings were found to be non-Gaussian. The accelerations had high kurtosis values, this can clearly be seen in Figure ?? and is, again, caused by longer periods where the drifters were stranded in shallow regions or stuck within the channel and did not move for several minutes.~~

, the histograms and numerical values can be found in the supplementary material. The mean values and the standard deviations ~~from Table 3 were~~ were then used to estimate the required sample size to achieve a precision of the sample mean to be within ±10% of the ~~true value~~ time-averages (i.e. $\varepsilon = 0.10$) for 95% of the time (i.e.$Z_{0.975} = 1.96$). The obtained sample size estimates were afterwards multiplied with the utility rates to estimate the required number of supraglacial and subglacial/englacial deployments. The mean pressure values were thereby corrected with the calculated air pressure of 941.8 hPa based on elevation (600 m) and air temperature on 07.08.2018. ~~As Table 2 shows, the~~ This calculation resulted in unrealistically high required sample sizes are unrealistically high(Table 2). These high numbers are however not necessarily an indicator of sensor accuracy, but rather an indicator of composed of several components: One part is caused by the sensor accuracy and technical problems causing high variations in the measured data. The second part of the inaccuracy is due to spatial and temporal flow variability both between deployments, but also along the flow path. The lowest required sample size was for the pressure sensors and the magnitude of the magnetometermagnetic field intensity magnitude. The latter should however also be corrected by the value of the local magnetic field strength and the number of required deployments is therefore likely to be higher.

Distance and similarity measures were used to test the repeatability of the datasets. All calculated values for every sensor modality and statistical measure (Chi Squared Error, Kullback Leiber divergence, mean average error, mean squared error and data ranged normalized root mean square) are close to zero, thus indicating a high repeatability of the drifter deployments (Table X in the supplement). Our calculations of the Pearson correlation coefficients confirm, that the two pressure sensors are redundant (Figure 4). Additionally there is a correlation between the pressure sensors and the Magnetometer Y readings. The other sensor modalities represent independent variables.

3.3 Statistical evaluation

Distance and similarity measures were used to test the repeatability of the datasets. The probability density distribution of each time series data set was compared with the ensemble probability density distributions of all data sets. Various measures can then give an indication on how much the two compared probability density distributions equal each other, meaning how similar they are. Zero values indicate that the distributions are similar and that the experiment is repeatable. For this study, the Chi Squared Error, the Kullback Leibler divergence (KLD), mean average error, the mean squared error and the data range normalized root mean square were calculated for every sensor modality and direction (n = 40). The results are provided in Table ??. The values are generally very low, indicating that the empirical probability density distributions of the single deployments do not deviate much from the probability density distributions of the whole dataset. The highest KLD values are the ones of the right pressure, the magnetometer in x- and z-direction, the acceleration in y-direction and the quaternions in w-direction. The values are however still very close to zero, thus indicating a high repeatability of the drifter deployments.

Ensemble statistical measures of comparison for all sensor modes. Shown are Chi Squared error (Chi), Kullback Leibler divergence (KLD), mean average error (MAE), mean squared error (MSD) and data range normalized root mean square (RMSD). Sensor mode Mean ChiMean KLD Mean MAE Mean MSD Mean RMSDPressure left Pressure right Magnetometer X Magnetometer Y Magnetometer Z Accelerometer X Accelerometer Y Accelerometer Z Gyroscope X Gyroscope Y Gyroscope Z Quaternion X Quaternion Y Quaternion Z Quaternion W

3.3 Pearson correlation coefficients

Table 2. Estimated multi-modal sample sizes for ±10% precision and a 95% confidence interval based on measured mean values and standard deviations from all deployments (n=40), as well as estimated sample sizes for supraglacial and subglacial deployments based on the utility rate and the measured mean values and standard deviations.

Sensor mode	~~Estimated sample size~~ Required sample size estimate	Supraglacial	Subglacial
Pressure left	2	3	4
Pressure right	2	3	4
Magnetometer X	1264	1732	2180
Magnetometer Y	531	728	916
Magnetometer Z	296	406	511
‖Magnetometer‖	3	4	5
Accelerometer X	479,603	656,991	826,902
Accelerometer Y	7259	9944	12,516
Accelerometer Z	1,382,976	1,894,488	2,384,442
‖Accelerometer‖	670	918	1155
Gyroscope X	115,419	158,109	198,999
Gyroscope Y	14,309,576	19,602,159	24,671,683
Gyroscope Z	301,182	412,578	519,280
‖Gyroscope‖	281	385	485

~~Calculating the Pearson correlation coefficients between the different sensor datasets establishes potential correlations between the different sensor modalities and directions and can thus indicate if modalities are redundant or if they represent independent variables. To classify the associations, a modified classification scheme from Cohen (1992) was used. Thereby correlation coefficients from -1.0 to -0.9 and 0.9 to 1.0 were classified as very strong association. Coefficients from -0.9 to -0.5 and 0.5 to 0.9 as strong association, coefficients from -0.5 to -0.3 and 0.3 to 0.5 as moderate association, from -0.3 to -0.07 and 0.07 to 0.3 as weak association and correlation coefficients between -0.07 and 0.07 were classified as not associated. The resulting correlation coefficients together with their association classifications are shown in Figure 4. This figure confirms that the two pressure sensors are indeed redundant. The results also show an interesting correlation between the lateral pressure sensors and the magnetometer in the y-direction. A moderate negative association exists between the magnetometer in the y- and z-directions. The quaternions also have a moderate negative association between then x- and y-directions, and between the w- and y-/z-directions. Most sensor modalities represent statistically independent variables. The exceptions were the redundant signals from the two pressure sensors and the magnetometer in y-direction.~~

3.3 Moving mean analysis and velocities

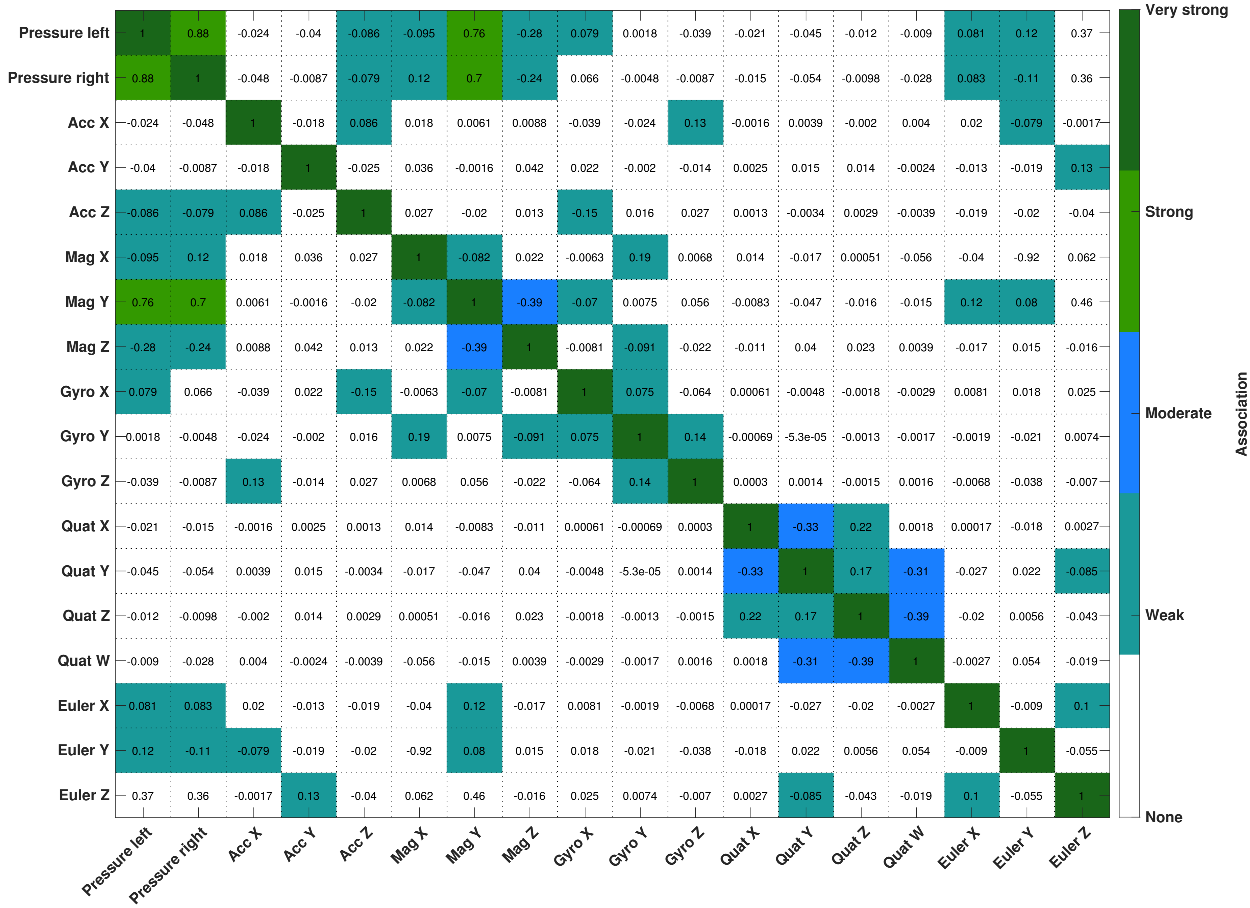

Figure 4. Pearson product-moment correlation coefficients (r) between the different sensor readings for all deployments (n=40). The classification is adapted after Cohen (1992).

~~The moving mean analysis with a 5 second rolling time window filters~~ After filtering out all short-term sensor fluctuations ~~and leaves only major signal features, as it can be seen in Figure 5. The plot shows the records of the two lateral pressure sensors It is clearly seen that the signals of the two lateral pressure sensors are almost identical, creating a redundant signal.~~

with a 5 s rolling time window a clear redundancy between the pressure sensors (Figure 5), as well as a close correlation between Magnetometer Y and pressure readings (Figure 6) become visible. As the experiments are conducted at atmospheric pressure conditions with only small elevation change over the passage, almost homogenous pressure signals should be expected. The plot in Figure 5 however, shows that the pressure records are displaying distinct variations including sharp peaks, sudden increases and drops. These variations are superimposed on a general increase of the pressure, which might be caused by the increasing atmospheric pressures as the drifters are flowing downhill, as well as increasing water depths in the channel.

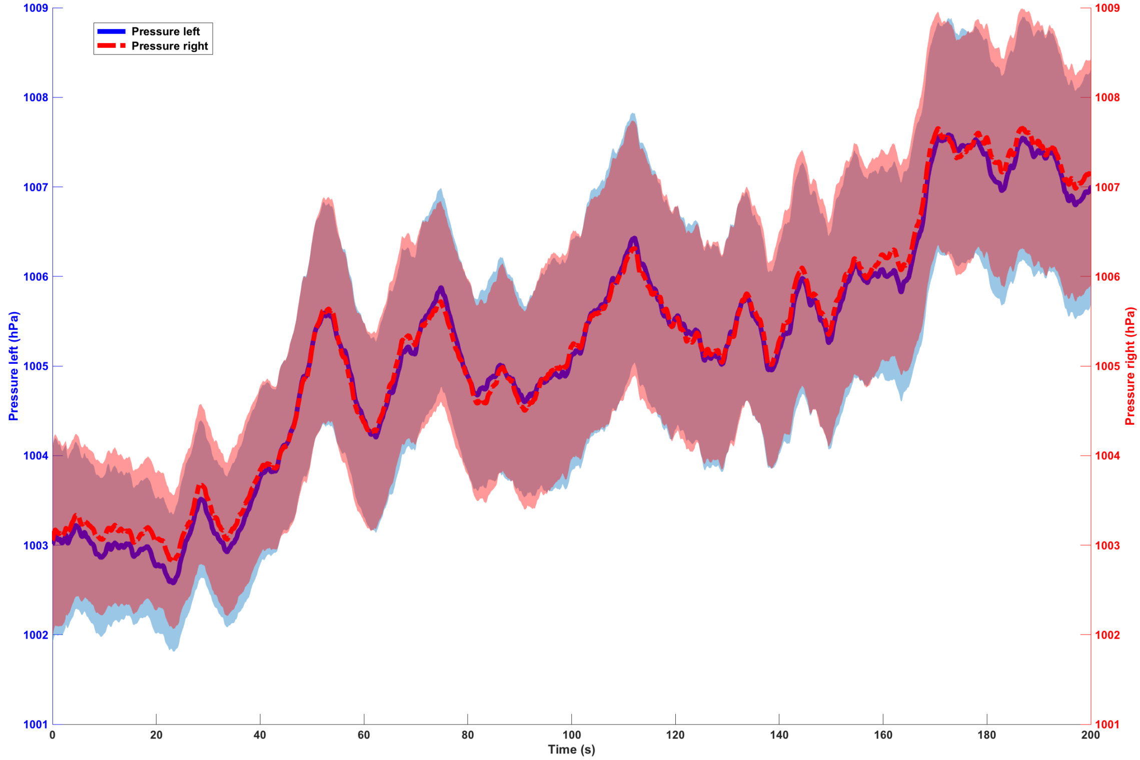

Figure 5. Mean values and 95% confidence interval (shaded area) of the left and right pressure over 40 deployments (n=40) over the first 200 seconds of the flow path passage. The data is averaged over a 5 s time window and across 40 deployments.

The 95% confidence interval CI of the averaged pressure signal can be seen to vary over time, but generally follows the same features as the average, with some features having smaller confidence intervals than others. The values of the 95% confidence intervals CIs are generally very low and on average do not exceed values above ±0.11% of the mean pressure value of 1005 hPa.

Left pressure and magnetometer in y-direction time series. The plot shows the first 200 seconds of 40 deployments (n=40), with a moving mean with a time window of and the 95confidence interval (shaded area). Figure 6 shows a close correlation between the moving means of the left pressure and the magnetometer in the y-direction. The y-direction refers to the y-direction being aligned with the longitudinal axes of the drifter, which is most often oriented along the flow direction.

The next plot in Figure 7 shows the left pressure together with the Plotting the magnitudes of the magnetometer, the gyroscope and the accelerometer averaged over a 5 second time window. Additionally the last panel showsthe magnitude

~~of the surface current speeds. All plots show~~ different sensor modalities shows, that the obtained signals are not homogeneous over time, but rather have pronounced signal variations, ~~and are~~ as also visible in the pressure signals.

~~Left pressure overlayed with the magnitudes of the magnetometer, the gyroscope, the accelerometer and the velocities, obtained from acceleration integration. The line is the moving mean with a time window and the shaded area represents the 95confidence interval of 40 deployments (n=40).~~ The width of the confidence intervals of all sensor modalities decrease after drifter deployment, vary however slightly over the time series, as the drifters pass through different channel geometries and flow features at individual velocities. The magnitude of the magnetometer has the second smallest 95% ~~confidence interval~~ CI with a mean confidence interval of ±2.45% of its' mean value of 54.6 µT. The other sensor modalities have larger confidence intervals with gyroscope readings being the next lowest on the list with a mean confidence interval of ±24.8% of it's mean value of 3.8 deg s^{-1}. The accelerometer has the largest confidence interval, and hence largest variation of recorded values, with a mean confidence interval of ±34.4% of its' mean value of 2.54 m s^{-1}.

3.4 ~~Velocities~~

~~Mean values and 95confidence interval of the three velocity components and velocity magnitude of 40 deployments (n=40) over the first 200 seconds of the flow path passage. The data is averaged over a 5 second time window. Integrating the three-dimensional accelerations provides the velocities, which were then filtered by taking the mean value over a 5 second window as shown in Figure 8.~~ The velocities in the x-direction (sideways in the plane of the drifters longitudinal direction, see also Figure 1) alternate between positive and negative values as the drifters travel through a meandering channel (Figure 8). Velocities in the y-direction remained mostly negative and vary between fast and slow zones. The negative values in y-direction are due to the buoyancy adjustment of the drifter. Every drifter had one balloon attached ~~(see right panel, Figure 1)~~ to achieve neutral buoyancy. We observed that the currents lead to the balloon flowing slightly ahead and the drifter facing away most of the time, thus leading to negative accelerations and velocities in the y-direction (longitudinal direction of the drifter, see Figure 1). In the z-direction (downwards facing from the drifters longitudinal plane, see Figure 1) the velocities remained mainly positive and vary between zones with slower and faster flow.

The magnitude of the velocity shows several pronounced signal variations in the time series as well. Generally values around 2 m s^{-1} are most common. The mean value of the 40 deployments, used for acceleration integration, is 1.94 m s^{-1} and the mean 95% confidence interval is ±24.5% (n=40).

3.4 Signal features of a step-pool sequence

Video footage was taken periodically during the ~~deployments, and supports the interpretation of the sensor records in terms of channel morphological features. Figure 9 shows the moving mean plot (2.5 seconds time window) of the left pressure sensor of one drifter during the~~ deployment and allowed to isolate the acceleration and pressure record during passage of a small step-pool sequence ~~, which was corroborated by video footage from the deployment.~~

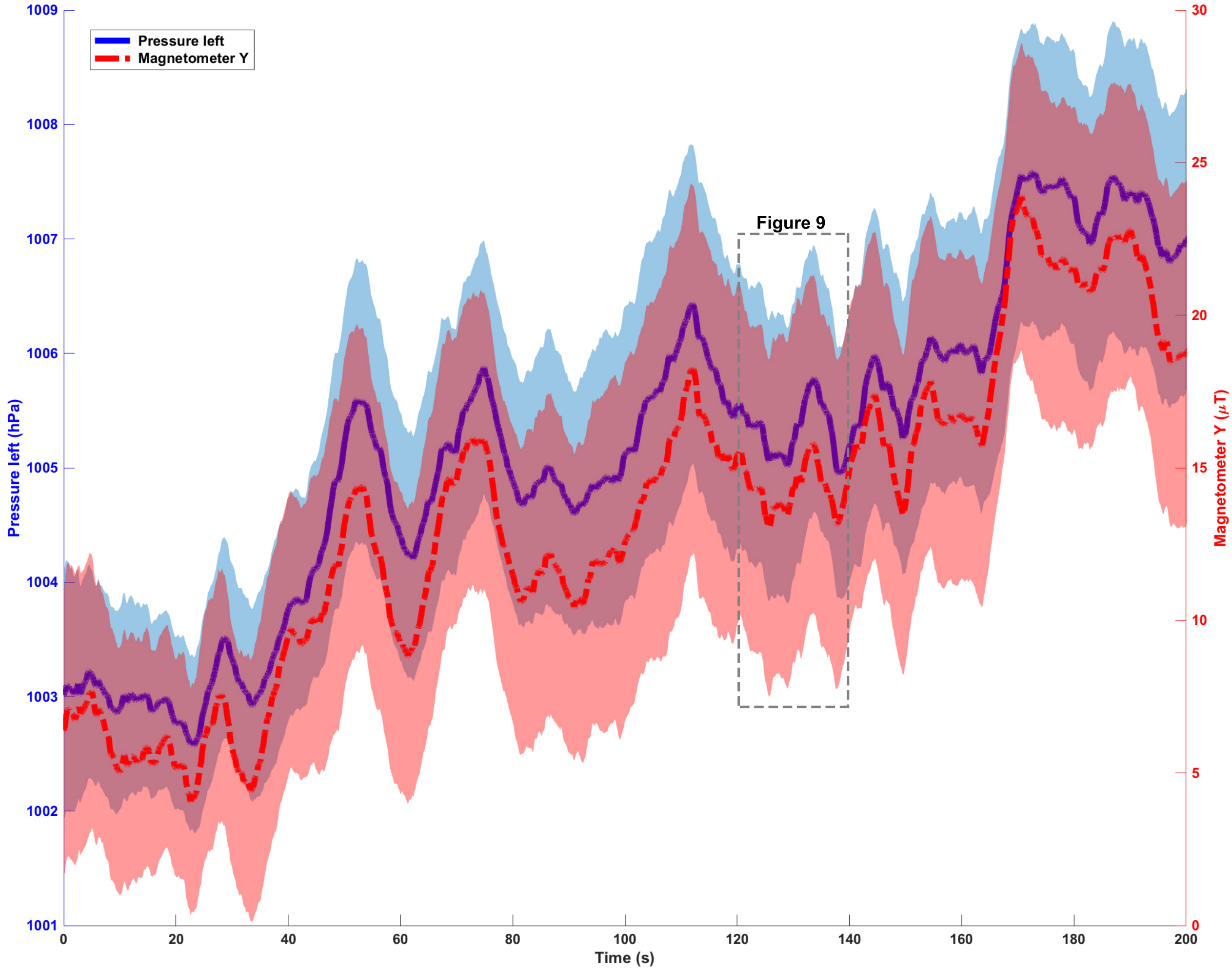

Figure 6. Left pressure and magnetometer in y-direction time series. The plot shows the first 200 seconds of 40 deployments (n=40), with a moving mean with a time window of 5 s and the 95% confidence interval (shaded area).

The moving mean plot of the pressure shows a (Figure 9). A pronounced peak, followed by a drop in the signal for the chosen time period, where the drifter passed over the step-pool sequence . The is visible. The pressure signal trails behind the acceleration signal. The video footage shows that the drifter was speeding up towards the edge of the step, when the pressure and the acceleration signal increased (Figure 9, A)). As the drifter flowed over the edge and dropped into the pool underneath, the pressure and acceleration dropped. Once in the pool, the drifter was caught in a recirculating current and remained in the pool for several seconds. This leads to a drop of the pressure signal, which stagnates signals, which stagnate at a lower level before increasing again, once the drifter leaves the pool and flows onward in the supraglacial channel.

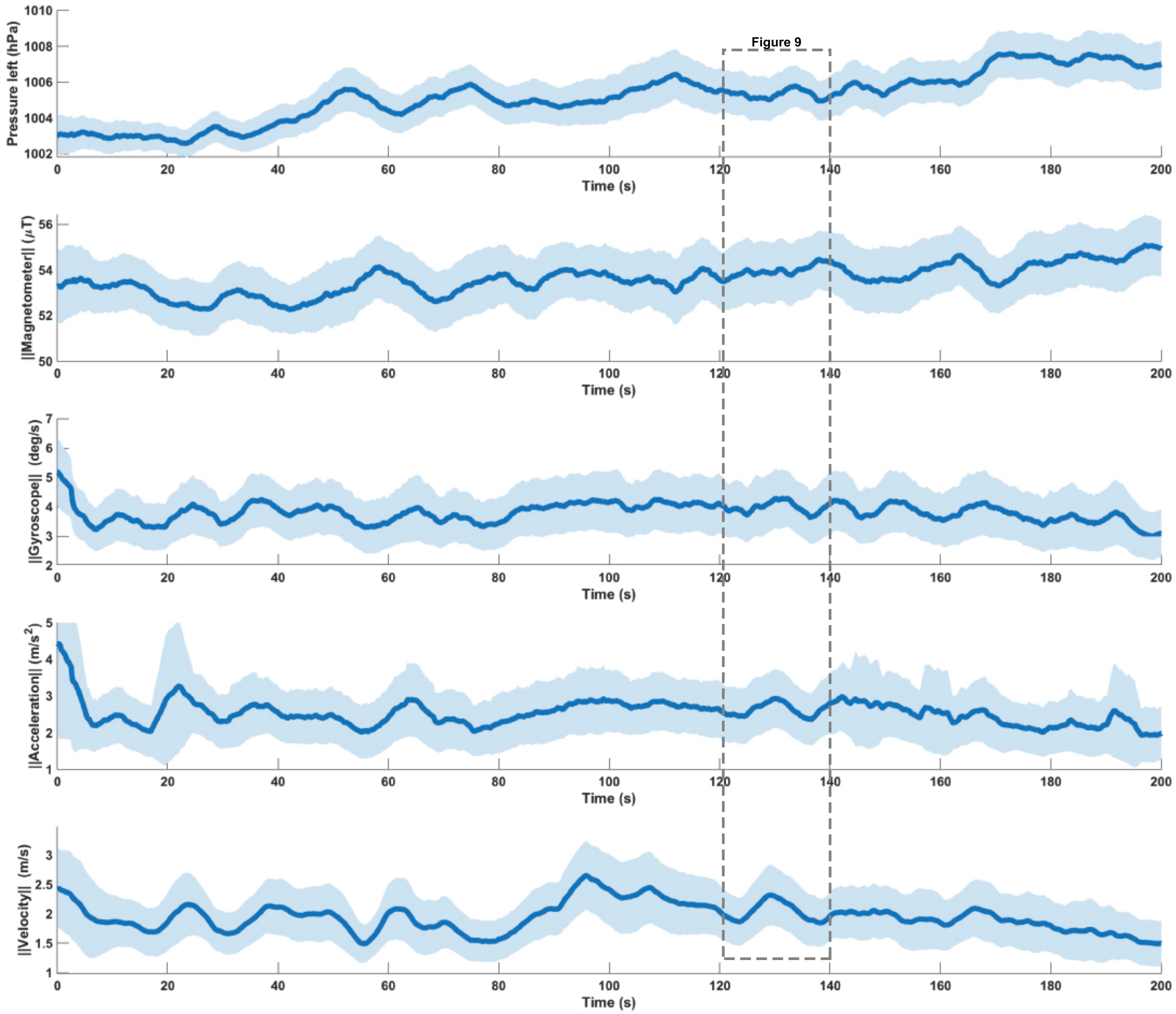

Figure 7. Left pressure overlayed with the magnitudes of the magnetometer, the gyroscope, the accelerometer and the velocities, obtained from acceleration integration. The line is the moving mean with a 5 s time window and the shaded area represents the 95% confidence interval of 40 deployments (n=40).

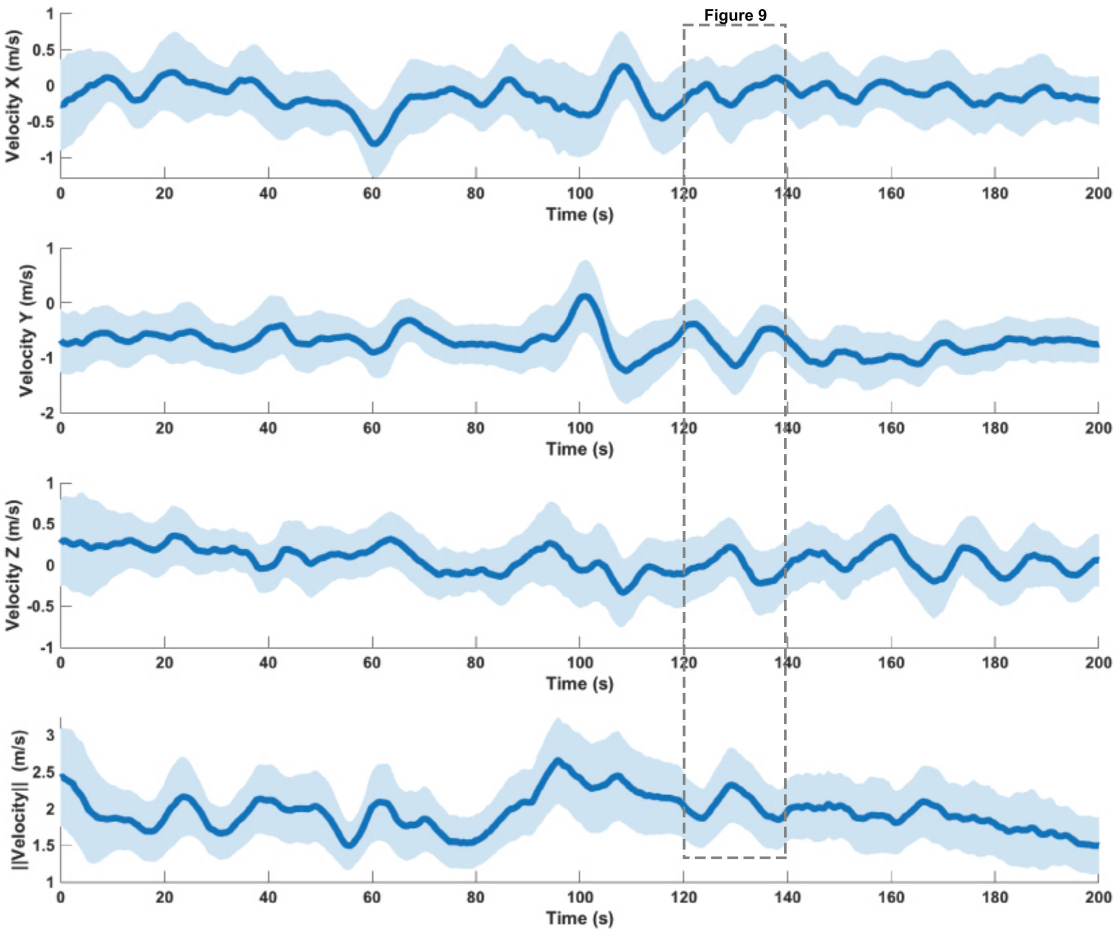

Figure 8. Mean values and 95% confidence interval of the three velocity components and velocity magnitude of 40 deployments (n=40) over the first 200 seconds of the flow path passage. The data is averaged over a 5 s time window.

4 Discussion

4.1 Drifter performance

An investigation of a glacial stream using sensing drifters generally ~~seems to require~~ demands a significant number of deployments ~~, as the values in Table 2show~~(Table 2), to allow for a statistical analysis and to account for drifter loss and technical problems, which are expressed by the calculation of the utility rate. Pressure values ~~will thereby be~~ are the easiest to acquire, as they need the lowest number of deployments compared to the much higher deployment numbers for the IMU values. However,

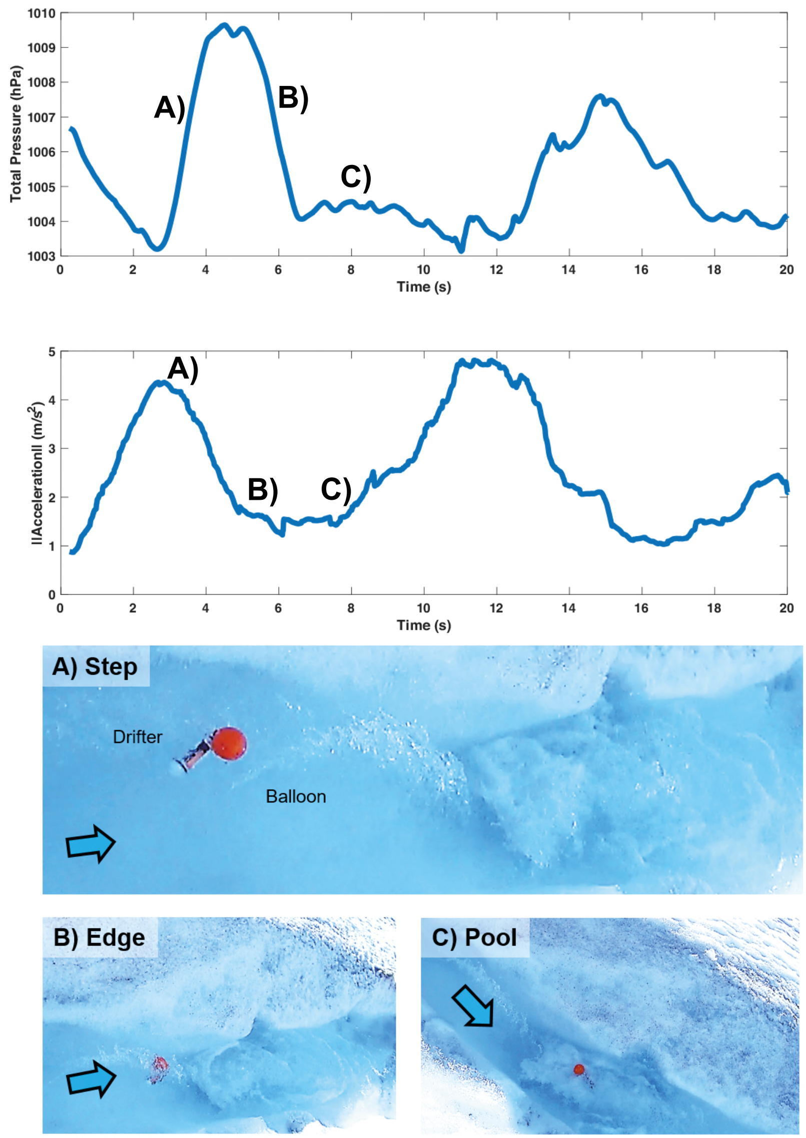

Figure 9. Exemplary data of a drifter going over a step-pool sequence. The plot shows the left pressure record as well as the magnitude of the acceleration from a single drifter, while passing over a step-pool sequence. The data is averaged over a ~~2.5 seconds~~ 2.5 s time window. Three zones are marked on the plot, which represent different parts of the passage. A) The acceleration and the total pressure ~~increases~~increase, as the drifter travels towards the edge of the step. B) The acceleration and the total pressure ~~drops~~ drop as the drifter flows over the edge. C) ~~Almost~~ Nearly constant acceleration and pressure values while the drifter is caught in an eddy inside the pool

the acquisition of flow data with sensing drifters in glacial channels will require an unrealistic amount of time in the field, and the deployment of many drifters simultaneously to reduce field time and the potential for external factors to influence the measurements (e.g. discharge variations). Bagshaw et al. (2012) previously showed that drifter passage through glacial channels can take several days to weeks, which imposes a practical challenge when it comes to acquiring several hundred to several thousand deployments for statistical analysis. In practice, this ~~is likely to mean~~ means that the measurements with sensing drifters will only be possible with ~~higher uncertainty thresholds ($p <$~~ lower statistical significance ($p \gg$ 0.05), as field deployments of several thousand drifters are not realistic. The number of deployments can however be reduced by decreasing the acceptable error, which is introduced by the sensor accuracy and technical problems, as well as through improved field deployment and recovery methods. Further technological improvements ~~may significantly decrease the number of necessary deployments, and an~~ of the sensor platform can reduce the signal to noise ratio of the drifters and the data usability rate. A problem with the proposed drifter platform was for example an occasional loss of battery contact in the battery holder due to high impacts, leading to corrupted data. This problem has been subsequently solved in an updated drifter system~~will be subject to field testing~~, which was field tested in summer 2019. The recovery during the presented field tests was done by the installation of a net inside the glacial stream. A method, that works well inside smaller supraglacial streams. It bears however the challenge of high ice (supraglacial streams) and bed loads (glacier outlets) clogging the net. This leads to the net damming up the water and hence allowing the drifter to flow over the net, requiring a regular maintenance of the net to prevent drifter loss. High discharge and flow velocities pose additional challenges and therefore require the further development of recovery methods.

The analysis of the moving means of the signals show that clear features become ~~visible~~ recognizable in some of the signals over the channel passage. The analysis of videos from the deployments show that these patterns seem to be related to geometrical features in the flow path such as step-pool sequences and recirculation zones. ~~More data will however be~~ We did however only record videos from thirteen deployments and did not measure channel geometries during this field experiment. More field studies with known geometry and repeated measurements of geometric features, which can be detected and classified in the signal time series and the channel geometry are therefore required to verify this hypothesis. Pressure sensors and magnetometer ~~in y-direction~~ Y seem to produce the most clear signal features. The pressure sensors have also the smallest 95% ~~confidence interval~~ CI of ±0.11% relative to the mean, and deliver the most repeatable data with the lowest error. The confidence intervals for all sensors remain more or less constant over time, some confidence intervals are however larger than others as the sensors travel with different velocities through the channel and pass certain geometric features at different times, which is not accounted for in the plot over time. A part of the higher confidence intervals also comes from the individual drifter movements, such as rotation rate, which are different for every deployment, hence leading to a higher confidence interval. It is however still possible to get pronounced signal features of the IMU readings as well, which can then be linked to geometric features of the channel and flow morphology, as shown in the supplementary video sequences. The IMU readings hereby give an extra value compared to a platform only equipped with pressure sensors, as they can provide the necessary extra information, which will allow us to further distinguish between different geometrical and morphological features of the flow and the channel respectively.

Multi-modal drifters with inertial measurement units present a potentially valuable tool to obtain three-dimensional accelerations along the flow path of a glacial channel. The integration of this data allows to obtain three-dimensional velocity estimates along the channel and to obtain transport surface velocities. This allows for a an initial, first order of magnitude estimate of the large-scale (> 10 cm) velocity distribution inside glacier channels, offering a large improvement compared to the state of the art, which relies on point velocities at certain locations through boreholes or integrated velocities along the flow path obtained from dye tracing. The velocities obtained from acceleration integration should however be further constrained with field measurements in future studies to deduce the error introduced by the integration. Nevertheless, the average 95% confidence interval CI of ±24.5% relative to the mean value clearly implies that further improvements are in order.

It can generally be stated , that the proposed multi-modal drifter platform provides satisfactory overall performance repeatable data considering the supraglacial field experiments at Foxfonna. The utility rate of 73% in supraglacial channels and 58% of the total deployments in englacial/ subglacial channels provides a first, reasonable estimate of how many sensors a practitioner should consider deploying.

4.2 Glaciological implications

This study establishes that multimodal sensing drifters equipped with pressure sensors and an inertial measurement unit present a new tool to obtain repeatable measurements in supraglacial channels. Further field studies are needed to interpret sensor time series to identify specific features corresponding to channel morphological types and flow conditions. The resulting signal features may be used to provide new insights into the dynamics of glacial hydraulics by overcoming the limitations of existing technologies, which are typically either restricted to a point location or yield only information integrated over the flow path.

We believe that multimodal sensing drifters can also be of great value for the modeling community by providing input for various models, like subglacial hydrology (e.g. Werder et al., 2013) or supraglacial channel development (e.g. Decaux et al., 2019). However, additional fieldwork using ground truth velocities as compared to drifter estimates are necessary. Once this is done, other important studies like linking subglacial hydrology measurements to glacier dynamics can be envisaged. Measurements using sensing drifters can be characterized by comparing them with other widely established measurement techniques, such as those listed in Table **??**.

Potential parameters of interest in subglacial hydrological studies and corresponding available measurement technologies. Parameter of interest Dye tracing Salt dilution gauging Borehole Trace gases GPR Gauging station Biogeo-chemistry Sensing driftersDischarge X X X X Average velocity X X X X X Channel location X XChannel geometry X X Pressure XXX Temperature XXX Flow path velocity X Water quality XX

5 Conclusions

The proposed multi-modal drifter platform tested in this work measures the total water pressure, linear acceleration, magnetic field strength and rotation rate while flowing along a glacial channel. The experiments performed during field experiments in this study showed that the platform used is able to obtain repeatable data in a 450 m supraglacial stream section. The data are not randomly distributed, but rather show distinct features, which after comparison with video footage of the drifters may be associated with changes in the channel morphology and flow characteristics of the flow. Linking distinct signal variations to channel morphology and flow properties may provide further insights into unknown channel geometries, e.g. in subglacial channels. The multi-modal drifter measurements appear however to require a significant number of repeated deployments to yield repeatable statistics at a 95% confidence interval. This is due to a combination of technical problems and potential deployment losses as well as natural flow variability. The latter Rapid changes in channel flows will always cause the obtained recorded signals to have variations between different deployments, thus contributing to the estimated significant some variations between deployments. We show that it is possible to estimate the number of deployments for some of the sensor modalities. Lowering the desired error threshold will however lead to fewer as a percentage of a given sensor mode's time-average value. It was observed that increasing the error threshold to above 10% of the time-average can significantly reduce the number of necessary deployments. Pressure measurements seem thereby most feasible for flow path feature detectionThe total pressure was found to be the most feasible measurand for repeatable flow path measurements in supraglacial channels, as they consistently had low the lowest error thresholds and high repeatability. The linear acceleration as measured by the platform, After low-pass filtering, the linear acceleration allowed for an estimation of flow velocities after integration, hence opening up for unprecedented detailed flow dynamic studies.This data may provide novel and rapid ways . An interesting finding was that the drifter data do not have random distributions, but rather distinctly non-Gaussian probability distributions. Comparison of time-series events with video footage of the drifters indicates that rapid variations in the drifter data likely correspond to changes in the channel morphology (e.g. step-pool sequence) and their corresponding flow characteristics (e.g. turbulent jet or recirculation region). We are optimistic that linking distinct signal variations to channel morphology and flow properties may provide further insights into unknown channel geometries, e.g. in subglacial channels. This additional information may provide new, more efficient means to investigate the velocity distributions within subglacial channels, after further calibrations of the sensor records to the flow features in glacial channelsduring follow-up field studies. Those field studies will together with further glacial channels. Future field studies including distributed velocity mapping will be carried out to further the technological improvements of the proposed platformlead to the availability of a new tool , with the long-term objective of providing a new robust, reliable and affordable device for glacial hydrological studies.

Video supplement. Sample videos of the drifter deployments in supraglacial channels can be found online as video supplements on the journal webpage.

Author contributions. AA, MK and JAT designed and planed the study. AA and MK conducted the fieldwork with support of AJH. AA analysed the data and wrote the manuscript. All authors contributed to the interpretation of the results and the manuscript.

Competing interests. The authors declare that they have no conflict of interest.

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