Dear Editors and Reviewers,

Thank you for considering our paper for publication in EGUsphere. We are especially thankful for the depth of the reviewer's comments. We have done our best to address these comments in our reply as well as in the updated manuscript.

In this reply, you can find your comments in paragraphs starting with "[COMMENT]" as well as our reply paragraph starting with "[REPLY]" below. If the manuscript was modified to address the comment, there will be a direct indication of the location(s) of the modification.

We thank you once more for your comments and for considering our paper for publication in EGUsphere. We look forward to your response.

Sincerely,
Felix St-Amour on behalf of the BRACHIOSAURUS team

**Reply to reviewer #1**

In response to the general recommendations, we are opting to follow suggestion "B" of reframing the paper as a record of a proof of concept. The details of the reframing can be found in our specific replies below.

[COMMENT] Lab conditions should be ideal conditions when you are testing your technology. If there are issues with this setup, it is hard to interpret field tests in less than ideal conditions. If the clamping was not done correctly, it would be best to redo your work so you can be sure of the data.

[REPLY] We attempted to improve the stake clamping in the lab with more rigid hardware, by anchoring against an optical table with strut channels, rather than using a bench vice. However, we found that the systematic error at short stake lengths remained at a similar level (2 cm systematic error at 100 cm pole length). We suspect that this remaining systematic arises from a small level of bending motion that passes through the clamping point. We could indeed make further attempts at improving the lab setup to reduce or eliminate this systematic. However, since the level of the effect is small compared to other systematics and uncertainties that arise in field settings (e.g., localized melt around the base of the stake, ice surface roughness and irregularities), we feel that the best way to proceed is to provide a recommendation that stakes have a minimum length of 1.2m. We have added the following text in the paper to clarify the above arguments:

- Section 1: “Existing automated ice melt monitoring systems cost upwards of $100 USD, while manual ablation stake measurements carry centimeter-scale uncertainties and local ice surface roughness introduces variations up to 10 cm. We therefore target an instrument costing under $100 USD with measurement uncertainty below 5 cm.”
- Section 5: “This discrepancy likely arises from limitations of the lab setup such as non-rigidity in the clamping point, which effectively increases the stake length and lowers the vibrational frequency. A perfect lab setup would enforce zero displacement and bending at the stake clamping point. Below 1.2~m, the differences between measured and predicted frequencies correspond to errors in derived length that span roughly 2--4 cm. This level of error lies below the target accuracy of 5~cm. Nevertheless, to minimize these systematic uncertainties, we recommend using stakes that support a first vibrational mode with a frequency below $\sim$7~Hz (which corresponds to a length of 1.2~m for the stakes described here).”

[COMMENT] Likewise, if you don’t have a surface to test the sonic ranger against, then get a sheet of plywood and a bracket to create one. Is there interference with the pole itself?

[REPLY] We have performed additional lab tests of the sonic ranger. The distance sensor deviates from the measuring tape distance measurements with a systematic error of -1.6 cm/m and a standard deviation of 0.5 cm/m. For a representative stake length of 2m, the corresponding systematic and statistical uncertainties are thus -3.2cm and +/-1cm, respectively. Throughout the lab tests of the distance sensor, we did not observe any evidence of reflections from the stake. Since the stake is thin and runs parallel to the sonic ranger’s nominal line of sight, we expect minimal reflections. We have added corresponding new text at the end of section 5:
“The HC-SR04 distance sensor was tested in laboratory conditions by placing the sensor along a measuring tape and evaluating the distance to a flat wall. The RMS of repeated measurements at fixed length was 0.21~cm, which is slightly better than the quoted specification of 0.3~cm. The distance sensor differed systematically from the measuring tape by $-$1.6~cm/m with a standard deviation of 0.5~cm/m. These effects are included in the distance sensor calibration and error computation for field data. Distance sensor measurements are also adjusted to compensate for the temperature dependence of the speed of sound, which is given by
\begin{equation}
v_s(T) = 331 \sqrt{\frac{T}{273}}.
\end{equation}
In this expression, the sound speed $v_s$ has units of m/s, the temperature $T$ has units of Kelvin, and 331~m/s is the speed of sound in air at

273~K~\citep{wong1986speed}. Throughout the lab tests of the distance sensor, there were no indications of errors caused by reflections from the stake."

[COMMENT] Testing should be first done thoroughly in the lab. Using a lake to test is an excellent idea. It doesn't need to be in the Arctic though. It could be near Montreal. Another option is to create a mound of ice with water. That ice can ablate over time during a test and this could be monitored closely. Close observation would be helpful before testing on a glacier.

[REPLY] We appreciate these suggestions and will plan on attempting additional frozen lake tests in future winter seasons. When we developed the small number of initial prototypes, we had the good fortune of having a window to conduct Arctic field tests soon after, thanks to our glaciologist colleagues, so we decided to jump at that opportunity. We are in the process of constructing additional units, and that increased hardware capacity will give us expanded testing options.

[COMMENT] It would be good to test both the accelerometer and sonic ranger against manual measurements. If your sonic ranger model is not good enough for a comparison, add one that is, at least for the testing. Other instruments and a timelapse camera would be great as well.

[REPLY] Thank you for these suggestions. Bringing in additional instrumentation such as a more robust sonic ranger or optical camera requires a nontrivial amount of engineering that is unfortunately beyond the scope of this paper. However, we will certainly aim to implement other automated cross-check measurements in future Arctic testing campaigns, as well as more frequent manual measurements. We are also considering implementing an improved sonic ranger for a future BRACHI revision, and we have added the following corresponding text in section 7:
"Future work will include validating the new design, including more detailed tests of temperature dependence, and additional field tests with more robust distance sensors."

[COMMENT] Using more than one stake at each length for field and lab testing is essential. This can be used to estimate error.

[REPLY] From the lab tests, where the stake length was varied between 0.85m and 2m, we found that the differences between the frequency-derived and manually measured lengths were less than the uncertainties on individual measurements. We therefore expect that stake-to-stake variation would also be subdominant to statistical uncertainties. The physical stake parameters that affect the resonant frequency, such as diameter and density, can be measured independently to reduce the associated systematic uncertainties.

[COMMENT] Temperature dependence should be worked out. Why is this happening? The effect needs to be isolated and removed or put in the error term.

[REPLY] We have conducted additional lab tests to assess the temperature dependence of the BRACHI electronics. We have concluded that the temperature-dependent effects in figure 6 are not caused by the electronics, and we have expanded the discussion of possible environmental explanations. The new pieces of text are:

- Section 5: “To test the temperature dependence of the accelerometer, a BRACHI unit was frozen to $-20^\circ$C and allowed to warm back to room temperature ($20^\circ$C) while oscillating on a stake of constant length and temperature. No temperature dependence was observed in the accelerometer data: throughout the test, the recorded frequency was stable within 0.1~Hz, which is consistent with statistical uncertainties at constant temperature.”
- Section 6.2: “Although the length data from $F_2$ have significantly smaller statistical errors, the apparent temporal variation may include temperature-dependent systematic errors caused by environmental effects. For example, solar warming of the stake may partially heat the ice at the base, altering the boundary condition and the frequency of oscillation. The BRACHI electronics are excluded from causing this systematic effect, since the accelerometer measurements vary by $\lesssim0.1$~Hz over the full operating temperature range (\S\ref{sec:indoors}), corresponding to an error that is roughly 25 times smaller than the observed temporal variation in frequency. The temperature dependence of the stake stiffness is also excluded as a cause since the effect is already included in the calculations. Although further testing is required to fully explain the apparent changes in length, the 1--2~cm level of variation is well below the target accuracy for BRACHI.”

[COMMENT] If there is no wind, there will be no motion to measure. How often do you anticipate there not being enough wind to get a measurement of F1 and F2? Or at least can you give some indication of the wind required to induce these frequencies?

[REPLY] This question unfortunately cannot be answered in terms of wind strength alone. First, stake oscillation is induced by changes in wind speed, rather than the average level, so F1 and F2 can be excited by a wide range of wind speeds (although higher wind speeds often have greater fluctuations). Second, a particular stake’s oscillation behavior also depends on its physical properties, including the exposed length. We nevertheless have attempted to describe qualitative effects of wind speeds on the presence and SNR of power spectrum peaks, and we have added the following new text in section 4:

“The peak at $F_1$ is usually present for nearly all accelerometer spectra, and the $F_2$ peak typically appears for longer stakes and stronger wind conditions. The signal to noise ratio (SNR) of the peaks is determined by the wind speed and the stake geometry, with stiffer stakes requiring stronger winds to achieve a good SNR. As a rough benchmark, the field tests presented in \S\ref{sec:outdoors} employ a 2-m stake that recorded data over a week. The $F_2$ peak is present during approximately 25\% of the measurements, and roughly 70\% of the measurements (both $F_1$ and $F_2$) have SNR greater than three.”

[COMMENT] Testing different brands of the same stake (pipe) will show how sensitive the method is to differences in manufacturing. What happens if the stake is slightly bent or damaged? Will that invalidate the measurement? At what point?

[REPLY] The theoretical curve of frequency as a function of length is fully determined by the physical parameters of the stake, such as the diameter and density, which are all parameters that can be measured independently. Small manufacturing variations can thus be directly measured and used to predict the frequency-length relation for any individual stake. The measurement technique cannot be used for bent or damaged stakes, since they are not described by the Euler-Bernoulli model that is assumed for this work. We unfortunately cannot give a general prescription for a level of stake damage that might be tolerable, since there are many different kinds of possible damage, and in each particular case, the stake properties (e.g., the Young’s modulus and radii) may vary both along the length and along the cross section. We nevertheless appreciate the importance of developing a specification for stake straightness, and we will aim to address this point quantitatively in a future publication. For the purposes of this initial proof of concept, we have added the following text in section 3:
“Any visible damage or deformations to the stake will invalidate the relation between the length and frequency modes. Intact stakes have self-consistent length measurements across all modes, whereas damaged stakes have different length measurements between frequency modes.”

[COMMENT] How easy is it to use a different kind of stake? Can users easily recalibrate to make use of steel, wood or plastic stakes? Glaciologists will need to know this to adopt the method.

[REPLY] Thank you for your reminder to include this point in the text. The frequency-length relation depends only on the geometry and material properties of the stake (e.g., Young’s modulus and density), so users are free to use stakes with a material of their liking and measure the properties to obtain the frequency-length relation. Many engineering websites have readily available data for the temperature

dependence of the Young's modulus for materials like steel, wood, and plastic. The density can also be found online. We have added the following text in section 3:
"The above calculations can be applied to hollow cylindrical ablation stakes with any dimensions and that are made of any material with known Young's modulus and density."

[COMMENT] What happens when it snows? Loose snow won't constrain the stake. Will dense snow constrain the stake vibration? At what point? Is there a way to use the sonic ranger to detect snow and account for it?

[REPLY] Loose snow does not constrain the stake and also allows the sound waves of the distance sensor to pass through. During the Arctic field tests, there was ~10cm snow accumulation on the surface of the frozen lake at the base of the 1-m stake (we have added this information to the text), and we confirmed that the snow did not affect our measurements. However, we acknowledge that additional tests are needed to assess the impact of denser snow. We have added the following text:

- Section 6.1: "The length measurements from the 1-m stake also suggest that the 10~cm layer of snow at the base did not constrain the vibrational motion, indicating that the ice layer determines the effective exposed stake length. Since this snow was loosely packed, further tests are required to understand the impact of other snow conditions."
- Section 6.2: "The distance sensor obtained readings that were consistent with the nominal 1~m stake length, thus suggesting that the sensor detected the ice at the base of the stake, rather than the 10-cm layer of loosely packed snow."

[COMMENT] What happens when the ice surface around the stake melts a little water-filled hole such that the stake is held firmly ~15 cm below the general ice surface?

[REPLY] Localized melt around the base of the stake is a source of systematic error, since the stake length that is subject to vibrations is determined by the location at which the ice fully anchors the stake. (The melted water itself has negligible impact because damping effects are proportional to velocity, and the oscillating stake has the lowest amplitude of motion near the boundary with the ice.) To minimize localized melt, we recommend that the holes for installed stakes be backfilled with water (rather than, e.g., ice chips) that has the opportunity to freeze solid. Localized melt will also be exacerbated when stakes are warmed by sunlight and conduct heat down to the ice. This effect can potentially be mitigated with stake materials and coatings that are less absorptive. We have added text addressing these points in section 7:
"The main sources of systematic errors in the field are related to uncertainties in boundary conditions where the base of the stake is embedded in the ice. For example, localized melt can lower the point at which the ice meets the stake, thus increasing the

effective length of the stake that supports vibrational motion. Further studies are needed to understand the types of boundary condition imperfections that arise in a wider range of field scenarios. Possible actions that can be taken to mitigate these imperfections include backfilling stake installation holes with water to allow the full volume to refreeze solid, and applying reflective coatings to stakes to minimize localized melt from solar warming."

Specific comments:
[COMMENT] Title: I think surface ablation is better than ice melt in the title

[REPLY] The title has been changed to "A low-cost surface ablation monitoring system using wind-induced motion of mass-balance stakes."

Abstract
[COMMENT] Surface ablation measurements of glaciers are critical for understanding mass change over → Surface ablation measurements are critical for understanding glacier mass change over

[REPLY] This has been changed as suggested.

[COMMENT] depends sensitively on the exposed length, → depends sensitively on their exposed length,

[REPLY] This has been changed as suggested.

[COMMENT] Color Lake → Colour Lake (here and elsewhere in the manuscript – proper name with Canadian spelling)

[REPLY] This has been changed throughout the text.

[COMMENT] surface activity at any locations → surface activity at any location

[REPLY] This has been changed as suggested.

1. Introduction

[COMMENT] Hulth (2010) presents a draw-wire method, although the measurement is sensitive to only surface lowering and not accumulation --- I think your method and many of the others presented also cannot measure accumulation at least directly (since for mass accumulation, snow density needs to be known)

[REPLY] Here, accumulation was intended to mean "the increase in thickness of the ice layer" as opposed to the accumulation of snow. The text in this section has been changed to "surface lowering.”

[COMMENT] representing annual or seasonal summer and winter balances, respectively → representing annual or seasonal (summer and winter) balances, respectively

[REPLY] This has been changed as suggested.

## 2 BRACHIOSAURUS design

[COMMENT] , and a depth sensor (Figure 1 (b)). This sensor measure range. It is a sonic ranger and it measures distance. There is no quantity ‘depth’ being examined in this paper. I recommend you replace depth with range or distance.

[REPLY] This has been changed throughout the text. Depth sensor has now been replaced by distance sensor.

### 2.2 Depth [Range] sensor

[COMMENT] Sonic range varies according to temperature (which affects the speed of sound). Please explain how this is corrected for.
The sonic pulse will spread out with distance from the sensor. What is the angle that describes the cone of ensonification? How do you avoid having the pole interfere with this measurement?

[REPLY] We have added an explanation of the temperature compensation and justification that the stake does not cause interference in the distance sensor readings. The HC-SR04 has an ensonification angle of 15º. The new text in section 5 is:
“Distance sensor measurements are also adjusted to compensate for the temperature dependence of the speed of sound, which is given by
\begin{equation}
    v_s(T) = 331 \sqrt{\frac{T}{273}}.
\end{equation}
In this expression, the sound speed $v_s$ has units of m/s, the temperature $T$ has units of Kelvin, and 331~m/s is the speed of sound in air at 273~K~\citep{wong1986speed}. Throughout the lab tests of the distance sensor, there were no indications of errors caused by reflections from the stake.”

### 2.5 Circuit board...

[COMMENT] sensor ‘eyes’ → sensor transducers

[REPLY] This has been changed as suggested.

3 Vibrational frequency

[COMMENT] Equation explanation of symbols – please include the units of measure here as well.

[REPLY] The equation does not contain dimensional constants, so any units of measure can be used as long as they are self-consistent. We have added a sentence “The numerical constants present in the formula are dimensionless” to clarify this point.

[COMMENT] The mass of BRACHI (assumed here to be a point mass at the end of the beam)

[REPLY] This has been changed as suggested.

[COMMENT] Fig 2 caption – make clear that numerical solution is for extended mass and analytic is for point mass

[REPLY] The caption states that “The slight difference between the numerical and analytic solutions for F1 arises from treating BRACHI as an extended or point mass, respectively.”

4. Data acquisition...
[COMMENT] 10 equal length chunks of 12 s each
below the noise floor – can you explain what the noise floor is in this case and why you would not just eliminate data that is below it? I think it is a matter of rewording the sentence to be clearer.

[REPLY] The noise floor is defined to be the median amplitude of the spectrum. This detail has been included in section 4: "Analyzing these chunks enables identification of low-amplitude vibrational modes that may fluctuate above and below the noise floor across chunks, where the noise floor is defined as the median spectrum amplitude."

[COMMENT] Future measurements will save and process the motion of all axes separately without squaring. - This needs to be explained (why) and moved to a better place (Future development section?)

[REPLY] The sentence has been extended to explain why squaring will be removed. The full sentence is now “Future BRACHI instruments will employ larger micro SD cards that can store data from all accelerometer axes; treating each axis separately, rather than using the squared magnitude, will simplify the spectral structure and the associated analysis.” We believe the updated sentence is best left in this section since later sections in the text do not explicitly discuss squaring.

[COMMENT] Local maxima that lie above the noise floor – define the noise floor.

[REPLY] The noise floor is defined to be the median amplitude of the spectrum. This detail has been included in section 4 (please see our earlier reply).

[COMMENT] Finding a candidate F1, determined by ...highest amplitude within a frequency range of 0 to 2F1 -- this seems rather circular logically. You need F1 to look for F1? !

[REPLY] We have updated section 4 with the following text: “The process of finding $F_1$ begins with identifying all peaks in the spectrum, defined as local maxima that are at least five times the global noise level and at least three times the local noise level. From this list of candidate peak frequencies $f$, the location of $F_1$ is determined by finding the lowest-frequency peak $f_i$ for which the corresponding amplitude is the highest between $0$ and $2f_i$.”

[COMMENT] By numerically propagating the errors from F1 and F2 – how do you determine the errors for F1 and F2? How are they propagated? In quadrature? Other? What happens if F1 or F2 can’t be found?

[REPLY] The sentence has been changed to "The error on L is obtained by numerically propagating the errors from F1 and F2 via the variance propagation formula." The errors on F1 and F2 are found as described in section 4: "The error on each averaged frequency measurement is taken to be the larger of the computed error on the mean, or the frequency resolution of the spectrum." When F1 and F2 can't be found, the length is not computed.

[COMMENT] Fig 3 – label the peaks adjacent to F2 as F2-F1 and F2+F1

[REPLY] This has been changed as suggested.

5 Lab measurements
[COMMENT] 2.7 g/cm^3

[REPLY] This has been changed as suggested.

[COMMENT] radii were respectively measured → measured respectively

[REPLY] This has been changed as suggested.

[COMMENT] Non-rigidity in the clamping point – please explain your set up here. Ideally you would redo it properly.

[REPLY] Please see our first reply, which discusses additional lab tests that we performed and new text that we've added to the paper.

[COMMENT] Analysis of higher-order modes, if present --- how often are they present? Under what conditions?

[REPLY] Please see our earlier reply, which discusses new text that we've added to section 4.

[COMMENT] Estimated precision of 0.25 cm – explain how you derive this? Is it variation in ice surface? Parallax error? Other?

[REPLY] The measuring tape was read to the nearest 0.5 cm, so the estimated precision is half that value. This text has been added in section 5.

[COMMENT] Although the depth sensor was tested qualitatively in the lab... I think you can do better!

[REPLY] Please see our earlier reply, which discusses new text that we've added to section 5 describing additional distance sensor tests in the lab.

6.1 BRACHI comparison against ...

[COMMENT] was below freezing and at a local minimum – what do you mean by 'at a local minimum'?

[REPLY] The sentence has been changed to "This test was conducted over a two-hour period when the ambient temperature was below freezing and at a minimum over a 24-hour diurnal cycle."

[COMMENT] Surrounding the stake is solid → replace with not actively melting

[REPLY] This has been changed as suggested.

[COMMENT] failed to detect ... degraded performance at low temperatures ... close to... operational limits – the temperature range is down to -20C but the temperature was not always close to this. Please look for another reason.

[REPLY] The sentence has been changed to "The distance sensors on the 2-m and 3-m stakes failed to detect the ice surface.  A possible explanation is a combination of degraded performance at low temperatures near the specified operational limits, the roughness of the ice surface returning a diffuse echo, and sound damping from the snow layer before reaching the solid ice."

[COMMENT] The BRACHI -derived lengths – there are 2 sensors to detect lengths. Please be specific

[REPLY] This was changed to "The frequency-derived lengths [...]."

[COMMENT] Temperature-dependent systematic effects – Yes, agreed you have some digging to do to explain how your system is impacted by temperature.

[REPLY] Please see our earlier reply about updating section 5 with additional lab tests that we have performed to study the temperature dependence of the electronics, and other possible temperature-related environmental effects.

[COMMENT] How are you measuring temperature? Can you measure actual ambient air temperature?

[REPLY] The "Accelerometer and temperature sensor" subsection of "BRACHIOSAURUS design" includes an explanation of temperature measurements, as well as the expected offsets. While the first version of BRACHI cannot measure the ambient temperature, additional sensors could be added to future designs.

Figure 6 –
[COMMENT] It would be good to know if you measured the length of the stake during this time. Maybe there was ablation?

[REPLY] Unfortunately, no manual measurements were done during this time.  We aim to perform more frequent manual measurements as part of future Arctic field tests.

[COMMENT] How are you computing the error bars in this graph?

[REPLY] All uncertainties and error bars on frequencies are computed as described in the "Data acquisition and analysis methods" section. From section 4: "The error on each averaged frequency measurement is taken to be the larger of the computed error on the mean, or the frequency resolution of the spectrum."

7 Conclusions

[COMMENT] I think you can only characterize your field tests as partly successful

[REPLY] We have removed “successful” from the first sentence of section 7, and the first paragraph of this section now contains a brief discussion of temperature-related systematic effects (please refer to our earlier reply for this text). We acknowledge that complexities related to the boundary conditions are one of the main limitations associated with the technique presented in this manuscript.

References:
[COMMENT] axel heiberg island canadian high arctic – capitalization

[REPLY] This has been changed as suggested.