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Interactive comment on "Tremor during ice stream stick-slip" *by* B. P. Lipovsky and E. M. Dunham

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1 Source radiation pattern

The calculation of seismic amplitudes in this paper relies on the assumption that the seismometer is situated vertically above the seismic source. In that case there is no P- wave radiation and S-waves only contribute to the signal. However, I find it very difficult to imagine that the observed wave field should consist mainly of this contribution. As tremor is widespread as stated by the authors and observed at many seismic stations, it should be unlikely that the seismometer sits in any case directly above the source. If the seismic source was only 800 m laterally away, S-wave radiation would be zero and the seismic signal should be dominated by P-waves. Known glacier

thickness compared with P-S travel time differences can in fact better constrain the position of the seismic source with respect to the seismometer. I would therefore recommend to additionally show one of the seismic signals where separate P and S-waves can be seen. This helps to validate the assumption made in your calculation.

P-S times have been analyzed by been done for this dataset by Winberry et al. (2013) in their Figure 3. They find P-S times $\sim 0.3s$. When $\nu = 0.33$ as is the case for ice, $c_p = 2c_s$. The observed P-S time therefore suggests an epicentral distance of 1200 m. At this epicentral distance, the reviewer is correct: P-waves should dominate in the seismogram instead of S-waves. If basal ice is more elastically compliant then this number could be more like 900 m.

Uncertainty in the epicentral distance and p- versus s-wave arrivals manifests itself in two ways. First, the uncertainty in assuming an incorrect epicentral distance will result in an error that is mapped directly into our estimate of the bed shear modulus. From Eq. (20) of our manuscript, we estimate that $G \approx 21.5 \pm 6.0$ MPa. If we instead take the epicentral distance to be 1200 m, then our estimate instead changes to $G \approx 27.9 \pm 7.8$ MPa. If the waves are assumed to be shear waves, then this difference corresponds to a difference of wave speeds of only 15 m/s or about 10%.

A more significant source of error is the error associated with potentially confusing P- and S-waves. Till has a large difference in P- and S- wave speeds. Unfortunately, it is not clear how to correct for this given the data that are available. Because it is not clear where the seismometers lay in the focal sphere it is possible that the stations are nodal for either p- or s-waves.

Given the data available, we do not think it is appropriate to fully simulate the propagation of P- and S-waves. We have modified the text of the paper (after Eq. 6) to reflect this understanding and point out possible bias in our source parameter estimates that arise from our assumptions.

2 Source dimensions

The described source process should be ubiquitous at the glacier bed or at least close to asperities. I assume that these asperities have larger dimensions than the calculated fault size of a few meters. How do signals from a larger area contribute to the seismic signal observed at one station and how may this influence the signal amplitude and shape?

As noted by Winberry et al. (2013), stations sometimes show multiple families of gliding spectral peaks, suggesting that more than one tremor patch is contributing to the overall tremor signal. Modeling multiple, possibly interacting tremor patches is beyond the scope of this paper. Furthermore, the events that we analyze in detail have seismograms/spectra (e.g., Fig. 3) that are dominated by one tremor source.

Assuming an asperity of the order of a few tens to one hundred meters, the observed seismic pulses may result from the superposition of P-and S-waves radiated from that area.

This is correct; see discussion above regarding P and S waves.

In Fig. 3A, there are several gliding frequency bands visible that must stem from a different source that produces different overtones gliding differently. How similar are tremor signals at the different stations. Can their variety be explained in terms of the model proposed?

These signals appear to be the superposition of another tremor patch. In other data (not shown) these tremor bands appear as low as 1-2 Hz. Multiple clear spectral peaks are seldom clearly visible for this source. Given the relationship $D = V_s/f_0$ of Eq. (3), these likely have slip as great as 1 mm. We have noted the existence of this other source at the end of Section 3 of the manuscript.

3 Seismic amplitudes

For calculation of maximum amplitudes of the tremor over time, you recursively find the highest amplitude peak in a 10 s window, meaning that you take the highest amplitude of one in a hundred peaks given a recurrence period of 0.1 s. From the seismogram example it seems that there is also amplitude variability of the order of 30% within an individual tremor sequence. How would you account for this variability as compared to the 30% larger amplitudes observed for double wait time events? It is unlikely that material properties or aseismic behaviour change at short time scales so there should be a different process that affects amplitudes. If you averaged the maximum amplitudes of all peaks in a tremor sequence (instead of taking the envelope), would the double wait time events still produce larger average amplitudes? That would strengthen your observation and rule out that there is larger amplitude variability within the tremor signal. The observation that these double wait time events produce larger seismic signals is very intriguing and therefore it would be great to expand on the description of this phenomenon.

This criticism inspired us to experiment with a different amplitude metric to verify that our amplitude measurements were not biased by our recursive peak finding method. The results indicate that even for a very simple measure of amplitude, the median of the absolute value of the trace, there is still a distinct difference in amplitudes between single and double wait time events. We describe this in the last paragraph before Section 7.1.

4 Technical comments

The abstract contains a few very technical expressions that make it difficult to under- stand for non-specialist readers. Examples are "state evolution distance" or "tremor seismic particle velocity amplitudes".

We agree that "state evolution distance" is a rather technical term, but one that is quite important and interesting to those studying friction. Because of its importance, and the lack of an easy way to explain it within the space limitations of the abstract, we have chosen not to modify how we use the term in the abstract.

With regard to "tremor seismic particle velocity," we removed that term from the abstract and instead now describe this as the tremor amplitude as recorded by seismometers. We retain the more precise terminology in the text, where it is clearly defined.

The seismic signal is described as being tidally induced, occurring twice a day at low or high tide. If both high and low tide can cause the signal, there should be four tremor episodes per day possible. Could you clarify this? (page 5256).

The tides beneath the Ross Ice Shelf are unusual in that the diurnal component of the tides is significantly more pronounced than the semidiurnal component. We have clarified this point.

The Poisson ratio in equation 13 is assumed to be 0.25 resulting in simplifications. However in Table 1 you use a Poisson ratio of 0.33 for ice and 0.49 for bedrock. How does that affect the validity of equation 13? Or vice versa what would be the consequence of using a Poisson ratio of 0.25 throughout?

In the limiting case where one material is much more rigid than the other, G_* becomes independent of the elastic properties of the more rigid material and $G_* \approx 2G_{compliant}$ for $\nu = 1/4$. When Poisson's ratio is chosen to represent ice ($\nu = 0.33$) and till ($\nu = 0.49$), the resulting effective patch shear modulus is $G_* \approx 3.5G_{compliant}$. We have changed the description surrounding Eq. (13) to reflect these points.

Fig. 1 Fig. 1 is not referred to in the text before Fig. 2.

The figure number ordering has been made consistent.

Fig. 1 shows 4 red dots, not three. It is therefore unclear which station is meant with BB09. Label this station as it is important. For clarity it would be better if all station symbols were coloured according to the sampling rate. The tremor stations could be additionally circled, boxed or otherwise highlighted.

We have made changes to improve the readability of Figure 1.

Fig. 3 A/B Explain the dashed white line in the caption and maybe mention the other gliding frequency bands stemming potentially from a different source.

We have made these changes.

Interactive comment on The Cryosphere Discuss., 9, 5253, 2015.