Reply to Referee #2 (Laurence Padman) on "Differential InSAR for tide modelling in Antarctic ice-shelf grounding zones"

Summary:

The reviewer is clearly an expert in tide modelling and provides invalueable insights in tidal dynamics, strengths and weaknesses of harmonic analysis as well as into the literature. The reviewer is right to point out that not the actual tide model physics are improved, but only (i) the tide model outputs are adjusted on the freely-floating part of the ice shelf by using DInSAR measurements (they are considered the absolute truth) and (ii) the adjusted tide model outputs are then scaled in the flexure zone by using 'the fraction of the tide-model signal that appears in the flexurally-constrained ice surface elevation signal' (aka alpha-map). The reviewer, however, seems to have misunderstood (1) the role of the two GPS records Shirase and Hillary in the analysis. Both of these records have only been used for validation purposes and don't feed into the tide adjustment/scaling algorithm. Similarly (2), it is true that t_tide only captures K1 and S2 as K1+P1 and S2+K2 without using inference, however, these harmonics have only been used within a short 16 day window and not in model simulations over an entire year (the reviewer agrees that 'an analysis without inference predicts tides within the window really well, but cannot be used to extrapolate'). Including inference in the analysis would be necessary if an entire year would have been modelled, but as only a relatively short window has been used to determine the rheology values, the errors in detecting the K1 amplitudes and phases from our 16 day tiltmeter records dominate the bias over the error due to inference (see reply to major comments below). We therefore focused our revisions on a more detailed uncertainty investigation of our harmonic analysis than including inference. We thank reviewer #2 for sharing his expertise in tidal dynamics and making us aware of using inference for analysing longer time series and leave the question on how to improve the actual tide model physics with an adjusted tide model output for future investigation.

Major comments:

1) Nomenclature : We extended the section on the sources of errors in tide models

2a) Inverse Barometric Effect (IBE) : The IBE is first calculated from barometric pressure records of nearby AWS and then added onto the raw tide model output. The result (IBE + tides + load tides) is then adjusted to match DInSAR measurements on the freely-floating part of the ice shelf. These adjusted tides are then validated with the independent GPS record Shirase. Afterwards, the adjusted tides are scaled using the alpha-map which is then validated with the GPS record Hillary. Note that both GPS records are solely for validation purposes. The alpha-map is a result of DInSAR alone.

2b) Dependency on time scales : We have identified that the most relevant control of the IBE is the window size over which to calculate a running mean of the barometric pressure. Our relatively long GPS record from the freely-floating part of the Southern McMurdo Ice Shelf was used to study the effects of changing the size of this window. First tides and load tides were removed from this GPS record to extract the IBE signal (called residual error). Second, the window length was varied linearly from 0 (instantaneous response) to 10 days (very delayed response) to calculate the IBE value in comparison to the residual error. Third, the RMSE is plotted as a function of the length of this window. Note that (i) the longer the length of the runing mean, the closer the IBE value is to zero; (ii) the shorter the length of the running mean, the smaller the RMSE with a best match if an instantaneous response is assumed:

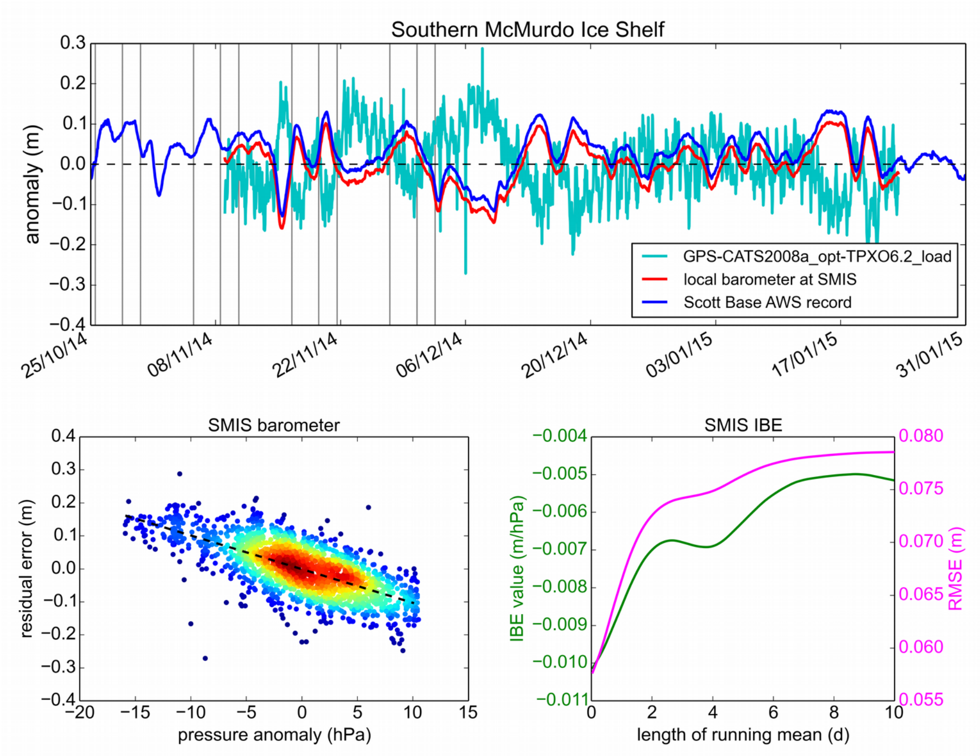
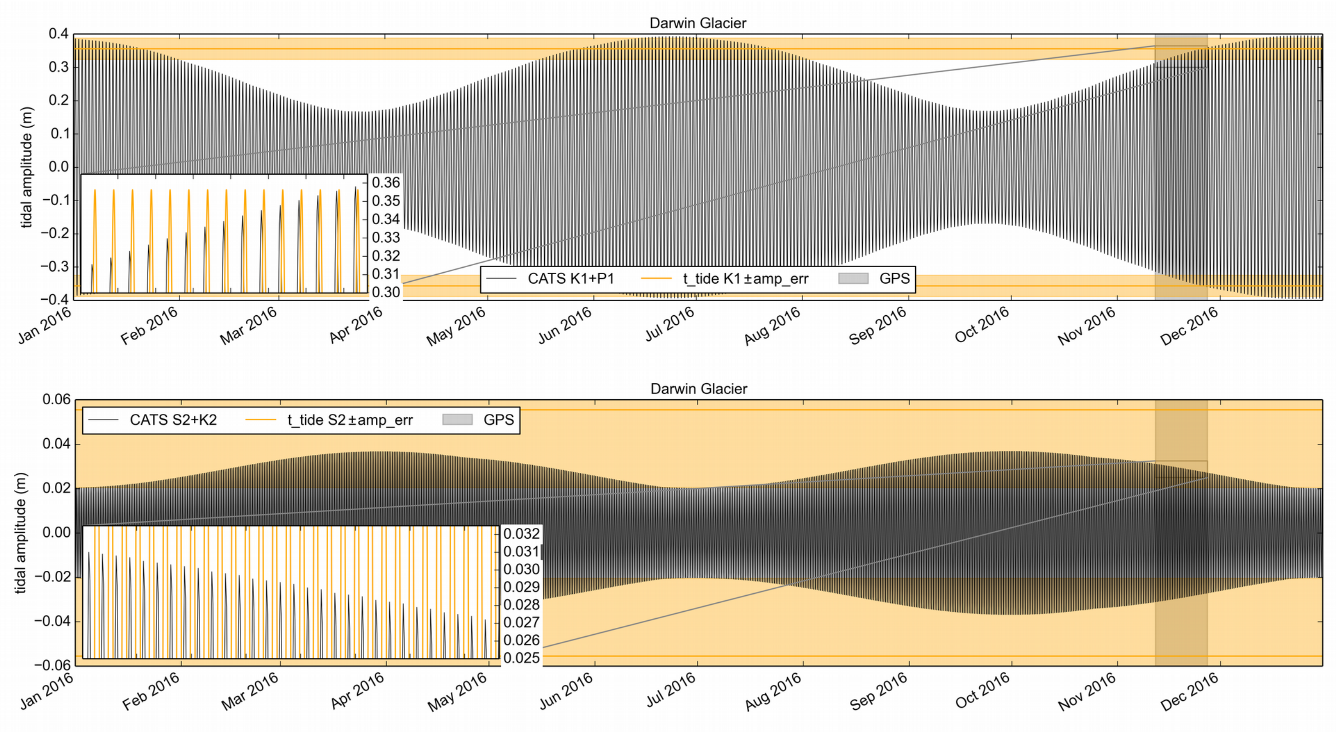


Illustration 1: Calculation of the best window size for the IBE: (Top panel) Comparison of the resiual GPS signal to two scaled barometric records (1 hPa = -1 cm). (Bottom left panel) Scatter plot of the pressure anomaly from a local barometer and the anomaly of the residual to calculate the IBE as a linear fit through the point cloud (points are color coded to point density). (Bottom right panel) The lenght of the averaging window to calculate the scatter plot on the left and the resulting RMSE to our measurements. Note that any deviation from an instantaneous response will increase the RMSE.

3) Here might be the misunderstanding. The method used to optimize the tide model (tide + load + IBE) relies on adjusting it to best match multiple DInSAR measurements on the freely-floating part. It is independent from the GPS records and relies on SAR data alone (plus tide model, load model and barometer data as input). The method is therefore unable to detect individual tidal components and only adjusts the sum of the ones that are used in the underlying tide model. See related point 5.

4) Inference : The reason why we focused on the K1 component within the 16 day window in the first place was that t_tide didn't find other components with a sufficiently high signal-to-noise ratio for further analysis. Within this window, t_tide's estimate of K1 plus/minus its amplitude error covers the variability that is introduced by K1+P1 wihin these 16 days (see figure below, top panel). These uncertainties as well as the phase errors of t_tide's K1 components now feed into the paper when we determine the Young's modulus and viscosity values. We note that using inference would be necessary if t_tide's K1 components would have been extrapolated to times when the K1+P1 inference is larger than K1's amplitude error (f.e. April and October 2016). Similarly, t_tide's S2 component shows large uncertainties. The range of its S2 amplitude error is much greater than the annual variability in S2+K2. For these reasons, the tuning of the model rheology focuses solely on t_tide's K1 components (now within respective amplitude and phase errors).



5) Correlation :
We weren't aware of the fact that tide models differ systematically between diurnal and semi-diurnal constituents. It would be very much appreciated if reviewer #2 could elaborate on which ones have generally good diurnals and poor semi-diurnals (and vice versa) and if this error is more likely to be in the amplitude or in the phase of the components. We agree with reviewer #2's hypothesis that this might explain why different tide models fit better to our diurnal-dominated GPS records, and note that Ross_VMADCP_9cm and Ross_Inv_2002 seem to lead the phase of the Shirase GPS record (Figure A1), while CATS2008a_opt and TPXO7.2 are in phase. From our experience in the Ross Sea region (Southern McMurdo Ice Shelf, Darwin and Beardmore Glaciers) we have learned that CATS2008a_opt is generally good in terms of phases, but underestimates amplitudes particularly during spring tides.

6) Phase errors :
It is true that phase errors in the tide model also affect the error to DInSAR fields. Is there a way to retrieve phase (and amplitude) errors from f.e. the CATS2008a_opt tide model, similar to the error bounds that t_tide provides ? We think that phase errors, and thus the timing of the tidal forcing, mostly affect the rate of tidal change rather than the absolute amplitude. An inaccurate phase would therefore influence the determined viscosity value. To minimize this uncertainty, we have selected the tide model with the best phase (Ross_Inv_2002) for the flexure modelling part of the paper and use the model with the best amplitudes (TPXO7.2) to reconstruct vertical surface displacements at the times of satellite overpasses (Section 3.1, 2nd paragraph). We hypothesize that our adjusted tide-model output can be used in the future to improve the actual tide-model physics (in terms of amplitudes and phases of individual components) by assimilation (similar to the reviewer's explanation of deep ocean tides under the TOPEX/Poseidon mission)

7) Minchew et al. (2017) :
Initially we have chosen to only mention this study as a direct comparison between Minchew's approach and ours is currently not possible yet with our limited availability of SAR data. We agree that including some of the lessons they have learned is beneficial for the paper.

Minor comments:

p.2, l34 to p.3, l2 : Baek and Shum (2011)
We changed the structure as requested and thank reviewer #2 for his explanation that even an accurate O1 will positively affect other components.

p.3, l.10-13 : Stammer et al., (2014)
We removed the very small error and the reference to Stammer et al. 2014

p.4, l.9 : Pawlowicz et al., (2002)
We included the reference to Foreman (1977) as requested

p.4, l.27 : perfect tide models
We have changed the sentence to weaken the statement about us demanding a 'perfect' tide prediction

p.4, l.28-29 : Wild et al., (2018)
We expand on the method to adjust tide model output as requested

p.6, l.7-8 : inference
We expand on the t_tide part of the analysis and thank reviewer #2 for his explanation of the problem and confirming that a prediction within a 16 days window is sufficient but should not be used to extrapolate (which is also our experience elsewhere, but using inference might be a solution to this problem).

p.6, l.25-28 : Hillary comparison
We agree that both are 'slightly above' but leave the wording as 'close to.., and slightly above' because +1.3cm and +4.4cm are still a bit different.

p.7, l.7-9 : Sources of errors in tide models
We elaborate on error sources of tide models near the grounding line (inaccurate bathymetry, wrong water column thickness, small-scale currents in the sub-ice shelf cavity, etc) and note that these uncertainties can be addressed by taking ice mechanics in the grounding zone into account.

p.7, l.24-26 : Discontinuities
We removed jargon.

p.8, l.29 to p.9, l.1 : K1 from a long record
We first use the adjusted Ross_Inv_2002 tide model (all components) to force the flexure models, we then extract the model solutions at the locations of the 7 tiltmeters. We then run t_tide on these solutions and compare their K1 components to the K1 components of the corresponding tiltmeters (now with amplitude and phase errors). As stated above, the K1+P1 inference is within these error bars. We therefore didn't use inference at this stage as we only look at a relatively short time window, when our 'K1 plus minus errors' is within the modulation of K1+P1 during these 16 days.

p.9, l.7-9: orbit alignment:
For the Darwin Glacier we acquired SAR data from only one track, for the SMIS we acquired SAR data from three different tracks. If the times of all satellite overpasses in a year are plotted against the prevailing tidal amplitude we can see that the observed tidal amplitude is only varying once throughout the year as stated in the text.

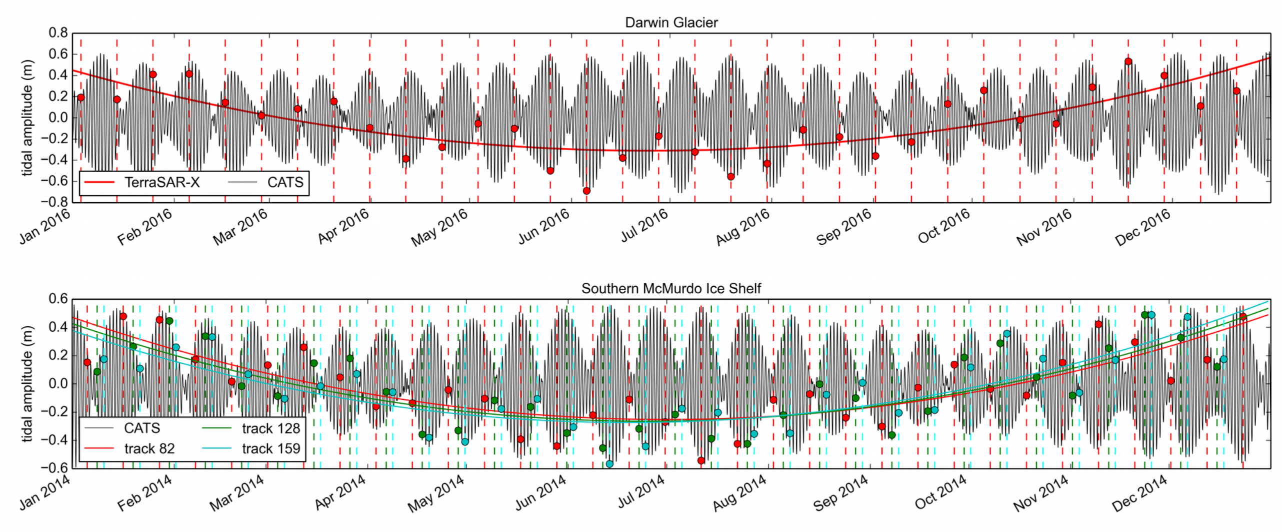


Illustration 2: Prevailing tidal amplitudes at the times of satellite overpasses of the TerraSAR-X satellite with an exact repeat pass of 11 days. Solid lines are a result of a 2nd order polynomial fit and show that the observed tidal amplitude varies only once throughout the year

p.9, l.20-21 : Phase
This is true, we state it now in the Methods section

p.9, l.26-28 : Viscoelasticity
We now defend this statement with a corresponding figure.

p.10, l.9-16 : Future work
Our long-term goal is to build on the work published in Marsh et al., 2014 who use inverse modeling of **elastic** tidal flexure to determine grounding-zone ice thickness from DInSAR. One idea is to invert a **viscoelastic** tidal flexure model for thickness, but this requires the use of tide models which aren't accurate enough yet to take advantage of the superiority of viscoelastic models. Another idea is to define criteria when an elastic model is sufficient to describe tidal flexure which would allow a purely elastic inversion of DInSAR. For this reason we would like to keep this paragraph in the paper but it was significantly shortened.

<u>Technical Corrections:</u>
1) Thank you for the explanation, we have corrected hyphens accordingly
2) We have tried to follow this suggestion as much as possible
3) We have changed 'heterogenity' to 'heterogeneity'
4) We have changed 'theta' to 'Delta A' in the text, tables and figures
Fig.1 caption : (a) changed as suggested (b) reworded the sentence
Fig.2 : changed as suggested
Fig.3 : changed as suggested
Fig.5 (now Fig.6) : changed as suggested
Fig.7 (now Fig.8) : changed as suggested
Fig.8 (now Fig.9) : changed as suggested and included label of Black Island
Fig.9 (now Fig.10) : changed as suggested
(new figure request) : the new figure has been included in the main text

<u>Other related changes to the manuscript</u>
All colorbars in the figures were modified to have a white background if they are displayed within individual panels.