Reviewer 1

General comments:

The authors have proposed a method to characterize the magnitude and timing of seasonal glacier ice velocity signals by fitting the best possible sinusoid to the velocity data obtained from optical remote sensing. It is well known that the optical data has obvious data gaps in polar regions during winters and is affected by cloud cover. This method is proposed to resolve seasonal velocity variations from such a dataset, but needs a large number of (>1000) multi-year velocity observations. The manuscript is well written, but I have a couple of points that may be useful to further improve this work. My major concern is about the applicability of this method to regions other than polar areas.

Major comments:

P5. I did not understand how observations over finite integration times make it difficult to resolve seasonal variability in case of repeat SAR imagery...

The sentence in question is from the abstract, and it previously read:

The task of generating continuous ice velocity time series that resolve seasonal variability is made difficult by the finite integration time over which ice velocities are measured...

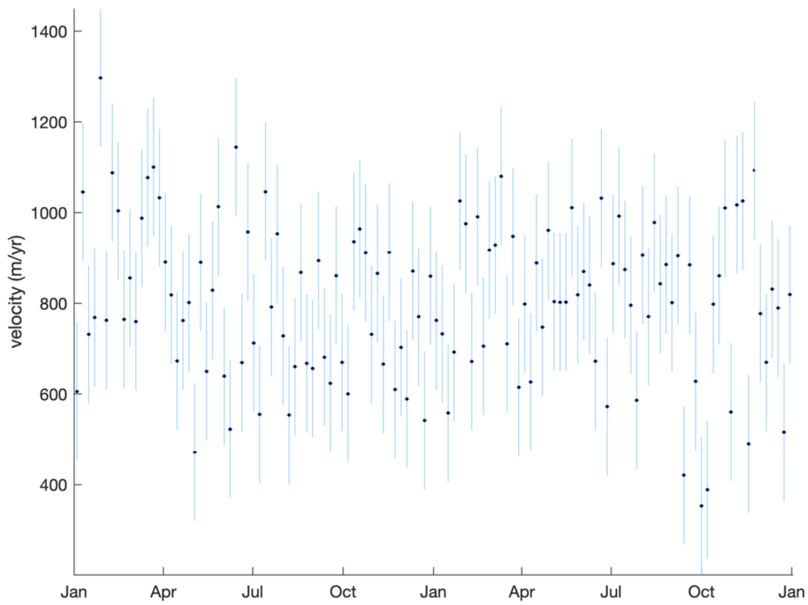
We have clarified the wording to more effectively convey that measurements of the total displacement that occurs over several months to a year will offer no direct insight into velocity variability that occurs within those months. The section now reads:

The task of generating continuous ice velocity time series that resolve seasonal variability is made difficult by a spotty satellite record that contains no optical observations during dark, polar winters. Furthermore, velocities obtained by feature tracking are marked by high noise when image pairs are separated by short time intervals, and contain no direct insights into variability that occurs between images separated by long time intervals.

...For instance, Sentinel-1SAR data is available throughout the year with a 6-day temporal cycle and a number of studies have resolved seasonality using SAR data (e.g. Sentinel-1, TanDEM-X)....

The 6-day Sentinel 1 repeat pattern does not reliably translate to continuous global coverage. Bandwidth limitations have resulted in minimal Sentinel coverage over Antarctica. Elsewhere, such as in southwest Greenland, SAR feature tracking struggles to correlate features between repeat images.

Even in the presence of perfect data coverage, short, 6-day integration times present their own challenges for feature tracking. Namely, the 1-10 m displacement uncertainty achieved with Sentinel 1 SAR image pairs is independent of image temporal separation. This translates to a velocity uncertainty on the order of 100 m/yr or more for an image pair separated by 6 days, meaning that any seasonal signals smaller than that would likely be difficult to distinguish from the scatter of the measurement noise. For example, here is a synthetic case of two years of perfect data coverage, without any missing 6-day image pairs. Here we synthetically measure a sinusoidal variation with an amplitude of 50 m/yr, but with gaussian displacement error (standard deviation 2.5 m) added to each synthetic measurement. Despite perfect coverage with 6-day image pairs, the 50 m/yr velocity variation is not clearly evident.



Matlab code to create the plot above is included at the bottom of this response letter.

...I think the focus of this paper should be optical data, its limitations during polar winters and cloud cover and how your method can still resolve seasonality using optical data.

The paper is focused almost entirely on optical data, its limitations, and how our method can still resolve seasonality using optical data. However, the method is fully agnostic to whether feature-tracked velocities were obtained from optical or SAR data, so we have been careful to write the paper in a way that does not preclude its application to SAR data.

P30-35. The authors should highlight these significant gaps which still limit our understanding of ice dynamics change on different time scales. I agree that a number of studies on the seasonal ice dynamics of glaciers in Arctic, Antarctic and other glaciated regions are available in bits and pieces, but they do provide a great degree of evidence that help us understand the physical processes which govern the ice dynamics on different time scales. I can't imagine how a consistent global mapping of seasonal ice dynamics looks like, which the authors have pointed to and how, if accomplished, they better our understanding...

The case for consistent, large-scale mapping can be made by drawing a parallel to Rignot et al.'s first comprehensive mapping of Antarctic secular ice velocity, which was published in 2011. Dozens of regional studies of ice velocity had already been published at that time, yet the application of a consistent measurement technique and synthesis into a single map has already informed nearly a thousand peer reviewed studies. We allude to the potential insights that could be gained from comprehensive mapping with this new sentence, which we have added to the end of the paragraph:

A comprehensive mapping of the world's seasonal ice dynamics would permit direct inter-comparison of seasonal evolution in regions with different driving processes; provide a basis for analysis of long-term changes in seasonal behavior; and supply models with a zeroth-order understanding of global ice climatology.

...It is also not clear why such an approach relies on optical imagery, even though we have a year-around consistent and global SAR imagery by missions like Sentinel-1. These points should be addressed in the Introduction to better form a basis or need for this study.

The method we present is not limited to optical imagery, and can just as easily be applied to SAR image pairs. Following this suggestion, we have now clarified that point in the abstract by stating,

In this paper, we describe a method of analyzing optical- or SAR-derived feature-tracked velocities...

We reiterate in the final paragraph of the Discussion section,

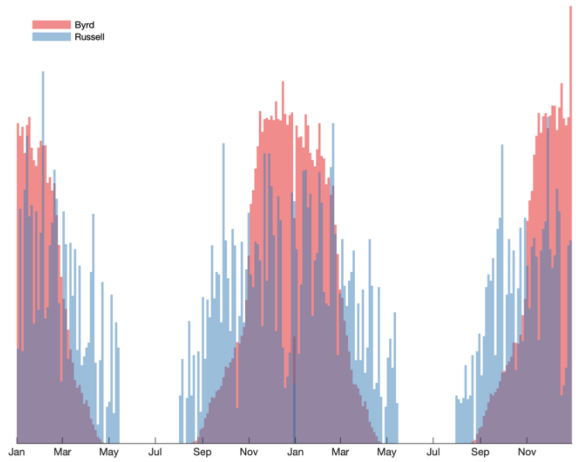
The methods presented in this paper have focused primarily on optical satellite data because no other type of sensor provides such a long record of ice velocity. As more radar data become available, particularly since the launch of Sentinel 1a/b, the problem of missing winter data will be eliminated, but the methods presented in this paper will still hold.

Figure 7. Nice figure. But when I compared this with Figure 4, I drew a couple of points that need to be addressed. ITS_LIVE velocity data for Russel Glacier in Greenland is much more dense and appears to be well distributed around the year as compared to Byrd Glacier, Antarctica...

The apparent difference in data density is likely just a matter of figure size. Figure 4 fills the entire page width, and as stated in the caption it shows 14,208 image pairs of Byrd Glacier. In contrast, the panels of Figure 7 are much smaller and show 5189 image pairs of Russell Glacier. We used the same linewidths and marker sizes in both figures, which likely makes the Russell Glacier data appear more dense, given the overall difference in size of the two figures. We include the number of image pairs in the caption to clarify this point.

...I wonder how such a large number of wintertime velocities are available in Greenland using optical data. Are they averaged for the entire polar wintertime?...

To be clear, no images have been acquired during any winter at Russell Glacier. This is also true at Byrd Glacier. Here is a normalized histogram of image collection times for both. We've offset the dates of the Russell Glacier images by 183 days to allow direct comparison:



The lower latitude of Russell Glacier (67N) compared to Byrd Glacier (80S) allows a longer image collection season at Russell, but still, months go by each winter without any image acquisitions. If we wish to inspect feature-tracked velocities directly, all we can do is infer average velocities between images captured in the fall and spring, and we display them following the standard convention of using a horizontal line to connect the acquisition times of the two images. We find horizontal lines alone create a confusing mess to inspect visually, so we place a dark dot at the center point of each line. The caption of Figure 4 states,

Light gray horizontal bars connect the acquisition times of each image...Center dates t_m are shown as dark gray dots for visual clarity.

In Figures 4 and 7, the horizontal bars that span winters and dark dots placed in their centers may create the impression that data are available during the winter, but that is simply a convention of displaying this type of data because, as far as we know, there isn't a clearer way to visualize it.

...I expect that this dense and well distributed velocity data is the main reason why you have a great sinusoidal fit here, isn't it? Because ideally the method should resolve the missing velocities in winters using the data points for the rest of the year. By the way, it appears to me that ITS_LIVE observations in case of Russel Glacier are already resolving seasonal variations without applying your proposed method. An example, where velocity data is sparse like for Byrd Glacier, would be much more convincing how well your proposed method can resolve seasonality...

There are only 5189 ITS_LIVE observations at Russell compared to 14,208 at Byrd. We do not have a years-long record of GPS at Byrd for comparison, but the robustness of our results there makes it clear that the signal is physical, it is persistent, and it can be resolved by our method using any random selection of 1000 or more image pairs.

The central problem our method solves is that velocity variability from feature tracking cannot be interpreted by eye when image pairs are separated by months or more. Figure 1 illustrates this point—the patterns that appear visually in the image pair data in Figures 4 and 7 do not necessarily reflect the underlying patterns of velocity variability, either in amplitude or in phase.

...Russel Glacier is the best case scenario (P270). An example from any mountain glaciers from Alaska, European Alps and high Asia would enhance the applicability of the proposed method. The optical data is available around the year in these regions and is only affected by cloud cover. At present the method is proposed to work in these regions, but the potential challenges are not highlighted.

Russell Glacier is not necessarily a best-case scenario within the global ITS_LIVE dataset. As far as we can tell, it suffers from rather typical image issues, including summer surface meltwater and cloudiness. It was selected for analysis only because of its known seasonality and the availability of a decade-long GPS record that we could use for validation. The least-squares method we describe does not suffer from winter data gaps, but it does not benefit from the gaps either. As we state in the abstract and in the main text, our method is *agnostic* to data gaps in winter.

Minor comments:

P5,25 or elsewhere. Instead of using "accelerations", I would recommend to use "velocity variations" because both acceleration and deceleration are governed by physical processes.

We have replaced the word *accelerations* with the term *velocity variations*.

P25. Can your approach resolve velocity changes during such short time-scales? If yes, you should highlight in the paper what additional information is required in your method in order to retrieve such signals. If not, there is no need to include it in the Introduction.

In this introductory paragraph we provide context for the timescales and physical processes that we aim to resolve. We indicate that some previous studies have reported on interannual variability driven by ocean forcing, while other studies have considered the effects of tides on glacier movement. The timescales we wish to resolve are in between fortnightly and interannual, but currently the potential influence of ocean forcing and tides on seasonal timescales are not well understood. We feel it is appropriate to provide this brief background to help readers place this our paper in the context of previous work.

Figure 1. Example-1 shows a hypothetical scenario, especially the velocity time series shown in blue. We have plenty of SAR data and derived ice velocities for the polar glaciers. What about showing a real case here?

Real cases are shown in Figures 4 and 7, but visually deciphering what's happening in them is nearly impossible. Rather than overwhelm viewers with thousands of image pairs, we created this simple (but mathematically precise) cartoon to illustrate the fundamental elements of the problem that we solve in this paper.

P45: satellite image pairs » optical remote sensing image pairs

The sentence in question reads,

The method we present applies to ice velocity datasets...which have been derived by feature tracking techniques applied to satellite image pairs.

As it is written, the sentence is correct because our method also applies to SAR image pairs.

P85: It is not clear how the weights are assigned here. Are these based on residuals?

Line 81-83 states,

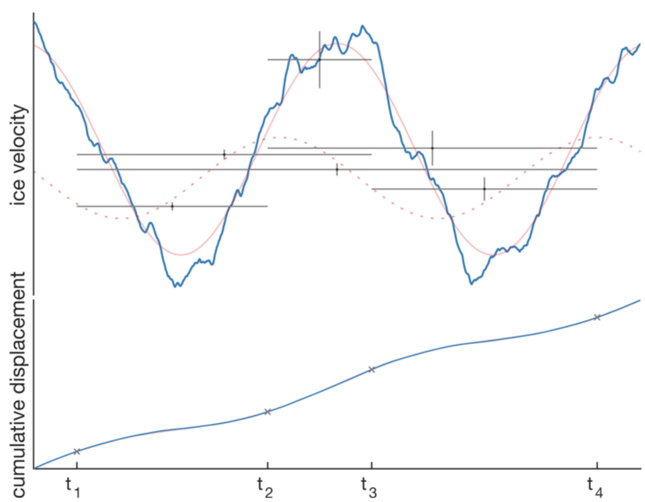
We assign the velocity weights w_v in the polynomial fit using the formal error estimates σ_v from the ITS_LIVE data such that $w_v = \sigma_v^{-2}$.

Figure 4: The colors (blue and green) in the legend and fits are inconsistent.

Fixed.

P105. "Instead, we operate on the displacements associated with each image pair, taken as the integrals of velocities" should be shown as a different figure as this is an important step of the paper. It would be better to see how various displacement estimates at different epochs ranging from days to years are prepared for any sinusoidal fit.

We have taken this suggestion, as we now plot the displacement time series along with the velocity time series to make it a bit more clear. Here is the updated Figure 1 and caption:



The upper panel shows an ice velocity time series in blue, which integrates to form the cumulative displacement time series shown in the lower panel. We use satellite images to measure ice velocity as the cumulative displacement of crevasses and other glacier features that occurs between acquisition times of any two satellite images. Here, four images taken at times t_1 through t_4 provide six unique combinations of image pairs that yield the measurements depicted as horizontal gray lines connecting the acquisition times of each image pair. Vertical gray lines *show measurement uncertainty and a black dot is placed at the center times of each image pair for visual clarity. A dashed sinusoid is fit to velocity measurements at the center times of each image pair to highlight the inadequacy of fitting directly to velocity data for determination of seasonal amplitude or phase. This paper describes an alternate, exact approach, wherein sinusoids are fit to accumulated displacements, which are then converted to velocity to produce the light red velocity sinusoid shown in the upper panel.*

P130. I recommend the authors to make a relationship between Va and Vs here. In other words, the authors should derive equation 4 from above equations or make a relationship between them. What is the goal here? Minimizing the Va?

We see that we failed to explain how we got to Equation 4. It is just the integral of Equation 1, but that was not made clear. We have modified the text, which now says

If our first estimates of A and φ are correct, then seasonal variability must have aliased each initial estimate of interannual variability by a certain amount v_a The amount of velocity aliasing equates the seasonal displacement over time, which we can obtain by dividing the definite integral of Eq. 1 by dt, or...

Matlab code

```
% Dates of first image for years of coverage every six days:
t = (1:6:365*2)';

% Dates of second image in each pair:
t = [t t+6];

% Displacement error in each image pair (m):
sigma_d = 2.5;

% Corresponding velocity error in each image pair (m/yr):
sigma_v = sigma_d/(6/365);

% Measurement noise:
v_noise = sigma_v.*randn(size(t(:,1)));

% Formal estimates of error (equates to 2.5 m in each image pair):
v_err = sigma_v.*ones(size(t(:,1)));

% "Measured" velocity time series with sinusoidal variation of 50 m/yr
% amplitude with a max value on day 91 of each year:
v = 800+sineval([50 91],t(:,1))+v_noise;

% Plot the results:
itslive_tsplot(t,v,v_err)
axis tight
datetick('x','mmm','keeplimits')
box off
ylabel 'velocity (m/yr)'
```