Interactive comment on "Seismic detection and tracking of avalanches and slush flows on Mt. Fuji, Japan" by Cristina Pérez-Guillén et al.

Anonymous Referee #1 Received and published: 1 July 2019

In this paper, the authors investigate seismic recordings generated by snow avalanches on Mt. Fuji in Japan. Signals recorded on a dense permanent seismic network are analyzed using the amplitude source location method (ASL) to track the flow path of the avalanches. While this method has been used to localize mass movements such as rockfalls, lahars or debris flows, it has never been used on snow avalanches. Using field observations and numerical avalanche simulations, the authors then estimate the precision of the localization. The paper is well written and structured and the results convincingly show that ASL can be used to track large and destructive snow avalanches. I recommend to publish the paper pending some minor revisions which are detailed in the annotated pdf.

Thank you very much for your constructive review. We have considered each comment and we have incorporated most of your suggestions in the revised manuscript. In the following, we reply to your comments:

1. You are not really detecting avalanches using the seismic network as you manually identified the signals in the data. I would therefore suggest to modify the title.

We suggest changing the title to:

Seismic localization and tracking of snow avalanches and slush flows on Mt. Fuji, Japan

2. Comment (Introduction). It would be good if you could explain the difference between dry-snow, wet-snow and slush avalanches in the introduction, and why this is important in the seismic context. Most of the readers will not be familiar with those differences.

We have added the following sentence in the introduction section:

Snow avalanches can adopt a variety of flow types from dry-snow avalanches, characterized by the typical powder cloud that usually hides a dense flow region, to wet-snow avalanches that are characterized by slower, plug-like flow. Slush flows are highly water-saturated avalanches that often entrain other types of debris. The ground motion generated is directly connected to the flow type of the avalanche (Pérez-Guillén et al., 2015).

3. Comments (page 4, lines 3 and 7). Regular depends on how you define it. You have 7 avalanches in 5 winters. Is this regular? Again, what does frequently mean for you? For me, it means at least a few times every winter.

At the present stage of our research we do not exactly know the frequency of avalanches and slush flows at Mt. Fuji. In this first stage of the investigation, we only searched for avalanche signals during three selected periods where we know that large avalanches had occurred. We are probably missing many events of smaller size. Based on our experience from other avalanche-prone areas in Japan and Europe, we consider it likely that on average several avalanches occur on Mt. Fuji every winter.

We have modified all the sentences related with the frequency of the avalanches. We changed the sentence

"Avalanches and slush flows, which release frequently on all flanks of the volcano, are the dominant natural hazard in Mt. Fuji's present period since its last eruption in 1707 (Original sentence)."

to

"Avalanches and slush flows, which appear to release almost yearly on all flanks of the volcano, are the dominant natural hazard in Mt. Fuji's present period since its last eruption in 1707 (New sentence)."

4. Comment on Figure 3. It would be more helpful to have an x-axis with time in seconds. You can put the date and time of the avalanche in a title above each spectrogram.

We decided to keep the same x-axis to avoid confusion with the x-axis of Figures 8 and 10, which are shown in seconds. In addition, the original labeling is consistent with the description of the temporal evolution of the events in the text (Section 2.3) and Tables 1 and 3.

5. Comment (page 7, line 17). Is this the method you use to determine the duration of the events? This should be more clearly stated in the text. Also, 505 s seems very long for an avalanche. Perhaps you can mention this in the discussion.

We have added the following sentence:

"The duration of the seismic signal is defined as the time interval in which the envelope of the signal exceeded a signal-to-noise ratio of 2, which is 505 s at the station V.FUJD."

At the test site Vallée de la Sionne, large wet-snow and transitional avalanches (they start moving as a dry-snow avalanche and transform into a wet flow) with run-out distances from 1500 to 2500 m generate seismic signals lasting between 330 and 555 s (Pérez-Guillén et al., 2016). There are videos available of diverse wet-snow avalanches that move slowly for ten minutes or more. The avalanche #1 released on Mt. Fuji started as a dry-snow avalanche, moving fast until the impact on the road. A second surge was moving much more slowly behind the front and reached a longer run-out distance, which generated a seismic signal of such long duration.

6. Comment (page 9, line 11). This wording suggests that there is some kind of detection algorithm to identify signals from avalanches. Better to write that the high background noise obscures the avalanche signal.

We have changed the sentence:

"The stations V.FJTR, N.FJSV and N.FJ1V show high background noise that prevents detection of the flow event. (original)"

"The high background noise recorded at V.FJTR, N.FJSV and N.FJ1V is overlapping with the slush flow signal, hindering its identification. (modified)"

7. Comment (page 10, lines 12 and 13). It is unclear what this statement is based on. Can you provide supporting evidence?

The ASL method uses the high-frequency seismograms (>5Hz) generated by the recorded flows under the assumption of isotropic S-wave radiation. We selected the frequency band of 4–8 Hz because it is the highest frequency band that has enough energy on the maximum number of stations to apply ASL. Our recordings show that for most of the seismic stations the amplitudes strongly decrease for frequencies higher than 8 Hz as the source–receiver distances are large (> 1 km).

The next figure shows the power spectral densities of the seismic signals generated by the four identified events:

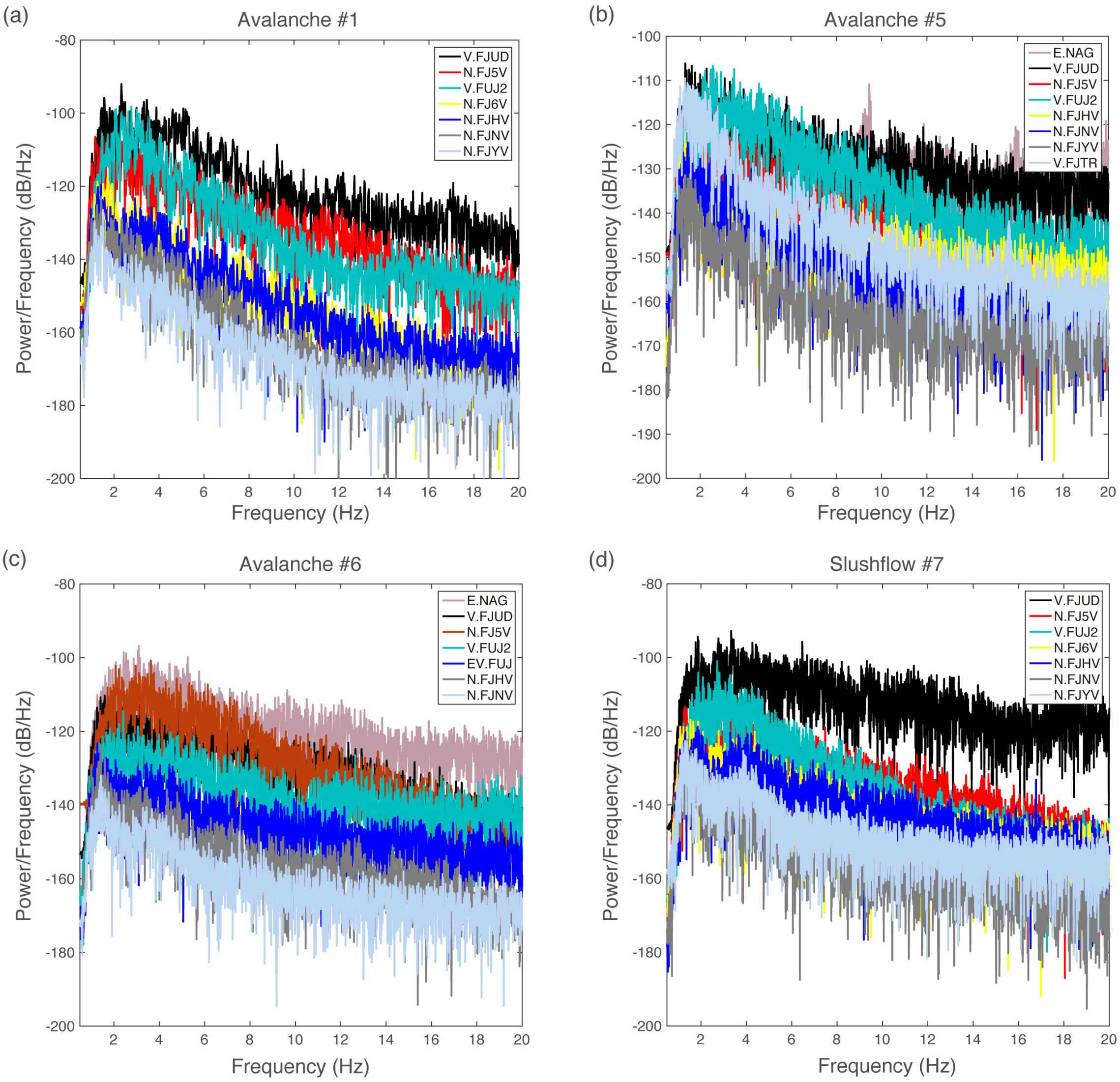

Figure 1: Power spectral densities of the seismic signals recorded at the different stations and generated by: (a) avalanche #1, (b) avalanche #5, (c) Avalanche #6 and (d) slush flow #7.

8. Comment (page 10, line 16). You assume this wave velocity. How sensitive are your results to this assumption? This should be mentioned in the discussion.

We tested the method for a range of S-wave velocities between 1300 m/s and 2000 m/s. The results are not highly sensitive to the variation of the velocity. We obtained minimum residuals for a velocity of 1300 m/s. However, we localized the flows with a higher precision using a velocity of 1400 m/s. We selected the latter one because it was also used by other authors (Ogiso and Yomigida, 2015; Kumagai et al., 2010, 2013) as a typical S-wave velocity near the volcano surface.

9. Comment of Figure 8. In this figure you use a different notation for your x-axis than in figures 10 and 11.

Yes, the time axes of Figures 9, 10 and 11 are based on the comparison of the seismic localizations with the starting time of the numerical simulations of each event. In this section of the paper, the seismic localizations have not been compared with the numerical simulations yet. Moreover, we did not perform simulations of events #2, #3 and #4.

We have changed the name of the x-axis to "Time" to differentiate it from the other figures.

10. Comment (page 15, line 17). I assume that the Digital Elevation Model (DEM) used has an influence on the numerical simulations. Please provide the details of the DEM you used.

We have used a Digital Elevation Model (DEM) of 5 m resolution for Titan 2D simulations. Extensive experience from numerical simulation with depth-integrated avalanche models like Titan2D or RAMMS indicates that a mesh resolution of 5–10 m is fully sufficient for reproducing the correct flow path and velocities. If high-resolution meshes (e.g., 1 m^2) from high-resolution DEMs are used, many codes tend to become unstable; moreover, the terrain description does not become more realistic in this way because the snowcover smoothens the landscape considerably up to length scales of the order of 10 m.

We have added the following sentence:

For Titan2D simulations, we have used a Digital Elevation Model (DEM) of 5 m resolution provided by the Yamanashi Prefecture and Mt. Fuji's Sabo Office of Ministry of Land, Infrastructure, Transport and Tourism (Japanese government).

11. Comment of Figure 10. Error is not the best term to use here. It is the difference between the model (which also has some uncertainty) and the estimates from the seismic localization. Suggest using another term.

We have replaced the term “error” by “precision” in the Figure and the text.

12. Comment (page 21, line 14). The wording here is rather awkward since you did not perform a correlation analysis.

We have changed the sentence from

“The knowledge of an accurate release time of the flows allowed correlating with the weather patterns that triggered them.” (original)

to

“Knowing the release times of the flows accurately allowed us to identify the weather patterns that triggered them.” (modified)

13. Comment (page 23, line 1). I also think that the deployment of the sensors can affect signal quality. The seismic sensor used by Hammer et al. was not installed close to the surface, as was the case with your sensors. Perhaps you can also comment on this.

We agree that the deployment of the sensors affects signal quality. Approximately half of our seismic sensors (NIED stations of Figures 1 and 5) used to localize the flows are also installed deep below the surface in boreholes at approximate 100-200 m from the volcano surface (Section 3.2) and sheltered from background noise.

14. Comment (page 23, line 8). You write mass flows, but you only talk about avalanches.

In line 9, we have changed the word “mass movement” to “snow avalanche”. However, we keep the title with the term “mass flows” because in the second part of this section, lines 21 to 31, we compare our results with previous applications of ASL to other mass flows such as lahars and debris flows.

15. Comment (page 24, lines 1 to 7). It is mostly a summary and can be shortened.

Ideally, the precision of ASL should be studied at an avalanche test site, where video recordings and radar measurements provide comprehensive information about the location and extent of the avalanche through time. However, no suitable seismic network is available at any of the presently operating test sites. At Mt. Fuji, only limited information about the location of the fracture line and the run-out area is available for four events (Fig. 2). Numerical flow simulations can fill this gap to some degree: The initial conditions---location and extent of the release area, fracture depth---as well as one to several model parameters can be varied independently until the deposit location and any other available constraints (e.g., extent and degree of forest damage) are satisfactorily reproduced. (original)

Ideally, the precision of ASL should be studied at an avalanche test site, where video recordings and radar measurements provide comprehensive information about the location and extent of the avalanche through time. At Mt. Fuji, only limited information about the location of the fracture line and the run-out area is available for four events (Fig. 2). Numerical flow simulations can fill this gap to some degree: The initial conditions as well as one to several model parameters can be varied independently until the deposit location are satisfactorily reproduced. (*modified*).

Anonymous Referee #2

Received and published: 9 July 2019

The paper by Pérez-Guillén et al. investigates the seismic signals generated by snow avalanches on Mt. Fuji, Japan. Seismic data are recorded by a permanent seismic network designed for volcano monitoring. Seven events are analyzed using the Amplitude Source Location (ASL) method. Aerial photos, field observations and numerical simulations are used to constrain the accuracy of the ASL. I agree on the comments and on the evaluation made by Referee #1. The paper is well written, the ASL methods is for the first time applied to show avalanches and results show that ASL can be successfully used to track large snow avalanches. I recommend publication after minor revisions, here following my main comments.

Thank you very much for your constructive review. We have considered each comment and we have incorporated most of your suggestions in the revised manuscript. In the following, we reply to your comments:

1. Title: I would skip the word “detection” to avoid confusion. Authors are tracking few events manually identified; they are not analyzing a continuous stream of data.

We suggest changing the title to:

Seismic localization and tracking of snow avalanches and slush flows on Mt. Fuji, Japan

2. Seismic dataset: Actually, most analysis are performed only on avalanche #1, avalanche #5, avalanche #6 and avalanche #7. I guess this is due to the availability of complementary information used for the validation of results. Please consider to clarify this point. Also, “(not verified)” and “?” in Table 1 can be misleading without an explication in both text and caption.

We have performed the same seismic analysis for all the avalanches. Unfortunately, we do not have photos or any additional data to conduct the numerical simulations of the avalanches #2, #3 and #4. In order to shorten the paper, we included the seismic signals of these avalanches and the analysis of the avalanche deposits observed on the historical images of Google Earth as supplementary material (esurf-2019-25-supplement). We have added an explanation in the text and caption of Table 1 to clarify this:

There is no visual data to verify the paths, release and depositions areas of avalanches #2, #3 and #4 (not verified events). (Caption of Table 1).

For these avalanches, no field observations or photos are available so the paths of these flows cannot be verified (Section 2.5).

3. Figure 1: Could you add graphic elements to highlight settlements and communication routes in the Mt. Fuji map? This would give some information on vulnerability to the reader.

We decided to keep the same map of Figure 1 and to add the main communication road of Mt. Fuji, the Subaru line, in the map of Figure 7.

4. Figure 7: I would suggest enlarging the map and maybe using different colors/markers for some events (e.g., grey markers of avalanche #6 blend with the background).

We enlarged the map and we replaced the grey markers by blue ones.

5. Discussion: I would deepen the discussion on seismic energy release and ASL comparing your results with those presented in other studies investigating seismic signals induced by other processes (i.e., rockfalls, debris flows, and lahars). Walsh et al. (2016) compared the seismic tremor amplitudes from a lahar to amplitudes generated from active seismic sources distributed along the drainage network to obtain estimates of lahar tremor location with ASL and energy release. In studies investigating seismic signals generated by rockfalls (e.g., Deparis et al., 2008; Levy et al., 2015), a scaling relationship between the duration of the process and its seismic energy and potential energy loss was shown. Coviello et al. (2019) proposed a scaling relation between kinetic energy and seismic amplitude indicating that for debris flows a little portion of the kinetic energy of each surge is converted into seismic energy.

We amplified the discussion part related with the seismic energy estimated for our events comparing our results with previous studies of seismic signals generated by other mass movements:

The two parameters deduced by the ASL method, D_s and A_0 (Table 3), can be used as quantitative measures of the event size as D_s is proportional to the maximum run-out distance and A_0 is linearly correlated with D_s (Fig. 13). In addition, another size-scaling relationship between D_s and the radiated energy was found. Previous studies found different scaling relationships between the radiated seismic energy and, e.g., the duration of rockfalls (Hibert et al., 2011; Levy et al., 2015) or the kinetic energy of debris flows (Coviello et al., 2019). We estimated the radiated seismic energy of the flow following the simplified approach used by Vilajosana et al. (2007b); Hibert et al. (2011). At volcanic areas, however, the diffusion model is more appropriate for modelling seismic energy transport as it reflects multiple scattering of the seismic energy due to the heterogeneities of the volcano (Yamamoto and Sato, 2010). The *maximum energy values estimated are in the order of 10^4 J (Table 3). These values are low compared to the estimated seismic energies (≈ 10^6 J) of two avalanches of size 4 in Norway (Vilajosana et al., 2007b), or with the estimated seismic energies of other types of mass movements such as lahars (Walsh et al., 2016), debris flows (Coviello et al., 2019) and rockfalls (Hibert et al., 2011; Vilajosana et al., 2008; Levy et al., 2015; Guinau et al., 2019), which range between 10^3 and 10^9 J depending on the type of flow and its size. In this study, we consider only a narrow frequency band of the spectra so that our values represent only a small fraction of the total generated seismic energy. Moreover, none of the previous studies corrected the seismic amplification due to site-effects before estimating the seismic energy. (Modified. Section 6.3).*