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Natural Hazards and Earth System Sciences
Discussions

Interactive comment on "Infrasound array criteria for automatic detection and front velocity estimation of snow avalanches: towards a real-time early-warning system" *by* E. Marchetti et al.

E. Marchetti et al.

emanuele.marchetti@unifi.it

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Reply to the interactive comment by E. Surinach (nhessd-3-C887-2015) on "infrasound array criteria for automatic detection and front velocity estimation of snow avalanches: towards a real-time early-warning system" by Marchetti et al.

Dr. E. Surinach performed a careful and detailed revision of the manuscript with many comments on specific aspects of the topic and organization of the text. We thank Dr. Surinach for this careful work as we think that revising the manuscript following

her comments allowed to greatly improving our work. Almost all the comments of the reviewer were addressed in the text and the manuscript was reorganized following her suggestions. Below we provide a point by point reply to here single comments.

Comment: The authors state that they present a new method. They mention that the method is based on array derived parameters and threshold criteria, considering avalanche as a moving source of infrasound. The authors must emphasize the novelty of their approach in the text. If this is not new, eliminate the word new in the abstract. Reply: The variation of back-azimuth and apparent velocity derived from array analysis of infrasound waves has never been used to identify automatically snow avalanches. This is clearly shown in the text. However the term new was removed in the abstract as requested by the reviewer, as it is not really important to be added there.

Comment: Instead of dynamic parameters indicate that velocity and back azimuth are derived. Reply: The word "dynamic parameters" was removed from the abstract.

Comment: The authors have to mention that events additional to those detected by the Doppler radar were obtained from their infrasound array measurements. Since this could be due to the different avalanche characteristics, perhaps a new conclusion could be incorporated. In this case, indicate it in the abstract. Reply: In the abstract we simply state that "We validate efficiency of the automatic infrasound detection with continuous observations with Doppler Radar", without going into the detail of the comparison. Adding here info of detected events with the two techniques, as requested by the reviewer, might increase ambiguity. Accordingly we prefer to maintain the sentence in the abstract more general, also considering that the topic is carefully discussed in great detail in the text.

Comment: Add that the criteria are area depending. Reply: This was added in the abstract as requested by the reviewer.

Comment: The introduction is correct; however, some changes must be made. L. 43 The authors mention e.g. the paper of Gubbler and Hiller, (1984) to illustrate detection

systems of avalanches. I suggest that the authors should mention the paper Rammer et al. (2007) Cold Reg. Sci. Technol. 50, 35–54. and Vriend, et al. (2013). Geophys. Res. Lett. 40, 727–731. For the purpose of illustration, the radars mentioned in these papers are more appropriate than the FCMW radar mentioned in the paper of Gubbler and Hiller, (1984). Reply: The reference was changed in the text according to the suggestion of the reviewer.

Comment: L. 59 The authors mention that the seismic observations provide the exact time of occurrence and that seismic arrays allow us to obtain an accurate location of the avalanche. I would be more prudent and eliminate the words “exact” and “accurate”. Seismic observations provide the time of occurrence, but not the exact time of occur rence and provide the location, but not accurately (if you use accurate, you must specify the accuracy).The literature leads you to this conclusion. Reply: The text was changed according to the suggestion of the reviewer.

Comment: L. 90 It is necessary to add “Kogelnig et al., (2011)” here. In this paper, a clear power spectrum of avalanche infrasound signal is presented, which will help the reader. Reply: The reference has been added in the text.

Comment: L.92 The authors state that the infrasound generated by the events mentioned have a similar wave form or that they can also be masked by different background noise. Note that the different events can be discriminated owing to the characteristics of their spectrograms. The authors must be more cautious in describing characteristics. Adding some references will help the reader (examples of different infrasound signals are shown e.g. in figs. 13 and 14 in Kogelnig et al, 2011). Reply: This sentence in the introduction is quite general and we prefer to avoid going into the details of the waveform characteristcs at this stage. This is discussed in great detail in the rest of the manuscript. What is highlighted here is that avalanches are typically associated to long-lasting emergent signals. These characteristics directly derive from the source process, being the source of infrasound a moving source with a given duration. We agree with the reviewer that spectral analysis can help, but in our expertise, there is

wide variety of infrasonic signals that can be recorded with an infrasound array, which are produced locally or regionally, and that share the same spectral content. Infasound produced by an avalanche is very similar in the waveform and in its spectral content to the signal produced by an airplane or by an earthquake at regional distances (200-300 km) or explosive sources at ranges of 1000s of km, where the propagation modifies the signal from impulsive to emergent and long-lasting. A wide literature describes this large ambiguity of atmospheric infrasound records and the book “Infrasonic Monitoring for Atmospheric Studies, Springer” and references hereinafter provide a good background of the topic. Given this similarity of atmospheric infrasound waveforms, much better results for source discrimination can be derived with array processing rather than waveform characteristics and spectral content. This is the main topic of the presented work.

Comment: L. 93 Specify the results obtained. Reply: This sentence has been expanded in the introduction as suggested by the reviewer.

Comment: L.94 Note that more than one avalanche occurred in the area (eg. in December). An avalanche is a natural process. Although in the literature the area of study is termed Grosstal avalanche (e.g. Kogelnig et al., 2012), I would be more precise and would mention the events as avalanches and the geographic situation of the area by its name (e.g. Grosstal avalanche area, or Grosstal avalanche zone). Reply: According to our knowledge and following the works by Kogelnig et al., 2012 and Jobst et al., 2014, with the name Grosstal avalanche the author refer to a specific channel, which is monitored by a Doppler radar and is thus used in this study to evaluate the efficiency and benefit of infrasound array observation. Anyway we understand the comment of the reviewer and change in the manuscript the term “Grosstal avalanche” with term “Grosstal avalanche channel”.

Comment: L.98 In this sentence, the authors qualify the parameters as kinetic, in other parts of the manuscript they are dynamic. As they are referring to angles and velocities, the term kinematic parameters must be used because no forces are involved. Reply:

We thank the reviewer for this comment as it was fully our mistake. Accordingly, we correct the manuscript and use the term kinetic/kinematic all along the text.

Comment: L. 101 It is not clear whether the aim of the authors is to describe one specific avalanche, the avalanches that occurred on the 23 December, or the area where the avalanches occurred, - If the purpose is to describe avalanche data, then indicate observations in the title: Grosstal Avalanche observations - If the purpose is to describe a geographical area, then the title would be The Grosstal Avalanche area. Reply: This comment is related to the comment of line 94. The term “Grosstal avalanche” identifies a specific channel and avalanche occurring there. For this reason we include in this section information of the area as well as of the event. We follow the suggestion of the reviewer and change the title accordingly.

Comment: I suggest reorganizing this section 2, describing the Grosstal area with all the instrumentation installed (2.1 and 2.2). I presume that the authors are interested in presenting the large avalanche on 23 December to illustrate the behavior of the instrumentation or the type of data obtained. In this case, the presentation of the data could be done after introducing the instrumentation. The authors have to indicate the type of avalanches that occurred in the area or the avalanches studied. Even though the interest of the authors is to present their avalanche detection system, it is necessary to include a paragraph indicating the type and size of the avalanches that occurred or that normally occur in the study area. This is an important piece of information to evaluate the detection system. For example, in figure 9 the 3 infrasound signals presented are different in shape, indicating a different type of process. There is no reference to this in all the manuscript. Reply: The main aim of the Section 2 is to present the infrasound array and radar observations available of events occurring within the Grosstal avalanche channel and compare results to identify pros and cons of the two techniques. For this reason we first focus on the event of Dec. 23rd, 2012, which is the largest event that occurred during the period of observation and then expand the analysis on all the available dataset. We agree with the reviewer that it might be useful

to add a paragraph describing the type and size of the Dec 23, 2012 avalanche but this is something that unfortunately we do not really have. The only report available on the event was realized by local officer (A. Siegele, acknowledged in the manuscript) in the morning of Dec 23, 2012. According to this repost, the avalanche started as a dry avalanche and was wet in the deposition zone, as it was raining at lower elevation. This information was included in the manuscript to provide all the available data to the reader. The rest is derived from our geophysical observations, which are presented in detail in Section 2.1 and 2.2.

Comment: L. 107 Please, indicate the characteristics of the 23 Dec avalanche. Reply: We added al available information about the event in the text.

Comment: L. 113 Add "Doppler radar". As different types of radar are used to study snow avalanches today, it is necessary to mention the type of radar in the title of this section. Reply: The title of the section has been changed according to the comment of the reviewer.

Comment: L. 129 Replace “depends on” by “corresponds to”. Reply: The text has been changed according to the comment of the reviewer.

Comment: L. 130 Note that there is only one event. Perhaps the authors confuse detections with avalanches. In this case, clarify the situation. Reply: This was a typo mistake, while there is absolutely no confusion between events and detections. This was corrected in the text.

Comment: L.124 and 132 Add "Doppler". Reply: This was added in the text.

Comment: L.135 In this section, you are describing information on the Grosstal avalanche area. To avoid misunderstanding, omit the word “Isggl” from the title. You can keep it in the text. The term “Ischgl” was removed from the text.

Comment: L. 143 Add “ including the Grosstal avalanche path”. Reply: The text was modified according to the comment of the reviewer.

Comment: I would include after L.170 the paragraphs from L. 233 to 245. These sentences correspond to data processing. The authors can also include some of the previous comments (L. 224-232) if they wish. From L. 171 The information of this paragraph does not correspond to data processing. It corresponds to a description of the results. I suggest incorporating this part into Section 3. If the authors need to include the signals in this section, a reorganization is needed. In L.191 there is also information directly connected to this. Reply: Following the comment of the reviewer Sections 2 and 3 were reorganized. Data are shown in Section 3 while the last paragraph of Section 2 introduces the main idea related to array observations of moving sources of infrasound.

Comment: L. 172 Replace “many” by “different" or "various”. Reply: Done.

Comment: L.174 Indicate _ N in all the angles. e.g. 309_ N to 330_N. Reply: Done.

Comment: L. 175 Note that it is “ values” not value. Reply: Sentence was rephrased.

Comment: L. 177 ...between: : :.. add “and the array location”. L. 178-180 Please, explain the difference between how you obtain 440 m/s and 460 m/s. Are all these values obtained from the array results? Please clarify. Reply: This point has been fully clarified in the text.

Comment: L. 183. Is the word “peculiar” the correct word? Reply: We changed peculiar with characteristic. Based on our expertise snow avalanches are indeed recorded with characteristic variation of wave parameters (back-azimuth and apparent velocity) and we use them in the manuscript to robustly identify events.

Comment: Section 3 This section must be rewritten considering the points below. As mentioned above, dynamic parameters are not inferred, only kinematic ones are. When studying avalanche dynamics (or kinematics) the knowledge of the size and type of the avalanche is necessary. The data presented in the paper show interesting information that the authors do not consider. Phase 2 has a spindle shape that differs from the one

of phase 1 (Fig.3). To understand better the information obtained from the infrasound signal, a description of the type of the avalanche is necessary. Reply: We completely agree with the reviewer, and wish in the future to have infrasound array observation of very well constrained avalanches. In this specific case, however, the information on the size and type of event is extremely limited and this prevents us to perform further speculations on waveform ahead of the infrasound-derived wave-parameters presented and discussed in the manuscript.

Comment: The three sections (phases) are very different, not only in their back-azimuth and speed but also in their amplitude. I would include all the results devoted to the 23 December avalanche (radar and array infrasound) and would also compare the results in this section. Reply: A detailed discussion on the three phases has been added in the text. This was developed in Section 4 when 3 events from the same path are extracted automatically and shown in Figure 8. See comment below.

Comment: L. 191 I suggest adding here the whole paragraph beginning in L.171. Reply: Sections 2 and 3 have been reorganized.

Comment: L. 193 Add "showing an energetic wave packet". The peak of pressure amplitude is important but so is its length and shape. Reply: Done.

Comment: L.198 Phase 3 presents apparent values of the sound propagation velocity of 330 m/s. The authors assumed 333 m/s for the sound speed (L.179). Reply: In line 198 we measure an apparent velocity (ca) of 330 m/s, while in line 175 we assume a sound speed (c) of 333 m/s. Please consider that c and ca are linked to the take-off angle according to Eq.1. In the case of the third phase of the avalanche the small differences is related to the fact that the takeâĂŤoff angle is almost 90°, being the array and the deposition area of the event at a similar altitude.

Comment: They also obtained an avalanche front speed of the 330 m/s from the infrasound array. A comment on the resolution of the system and its implications would be interesting. Reply: I think there is a bit of confusion here. In section 3.1 we estimate

the avalanche front velocity from the variation of back-azimuth with time. Velocity of the front, as estimated from the infrasound array, varies between 6 and 35 m/s. In lines 191-220, however, we describes values of the apparent velocity measured by the array, which is reflecting the propagation velocity of the acoustic wave produced by the avalanche (see Eq. 1 of the manuscript) and is not related at all to the velocity of the front.

Comment: L. 200 Please, explain the difference in the back azimuths and velocities obtained when considering an extended moving source or a punctual moving source. Reply: It is stated clearly in the text that infrasound array analysis allows deriving wave parameters of infrasound produced by the most energetic signal (lines 213-220).

Comment: L. 202 Please, explain this statement or indicate references to help the reader. Reply: This statement is actually our own conclusions, so no reference is actually required. We changed the text accordingly to underline that it is a suggestion we derive from observed wave-parameters.

Comment: L. 205-207 Please, explain this sentence a little more. First of all, the mentioned paper is devoted to pyroclastic density currents. The similitude between the two types of density currents must be explained or clarified with references. Reply: Based on our own experience pyroclastic flows and snow avalanches have many similar aspects in terms of infrasound signature and infrasound derived wave parameters. Several papers have been published by our group both on avalanches [Ulivieri et al., 2011] and pyroclastic flows [Ripepe et al, 2010 and Delle Donne et al., 2014]. To our knowledge, no theoretical or experimental comparison between the two processes is available in the literature. This sentence is derived from the analysis performed by Delle Donne et al., as it was shown that a flow (pyroclastic flow) entering a valley (so in case of a change of topography) tends to radiate infrasound from a stable position. In case of the paper by Delle Donne et al., infrasound observation was compared to infrared thermometry and this allowed clearly monitoring the front evolution through time. This was not possible in our work, as the only observation available is derived

from Doppler radar.

Comment: In addition, a shape and azimuth similar to those of phase 2 of avalanche 2012/12/23 (Fig. 3) are also observed in avalanche 2013/03/11 (Fig. 8 c). However, this part is observed before the energetic part. An explanation of this characteristic must be given. Reply: The 3 events included in Figure 8 share the same infrasound wave parameters and therefore are extracted automatically and are inferred to occur from the same path. Together with infrasound wave parameters (back-azimuth and apparent velocity) the 3 events share also a similar waveform, with two main phases. The only difference is in the amplitude ratio, with the Dec, 23, 2012 events peaking amplitude in the first phase and the March 11, 2013, event peaking in the second phase. However, in terms of absolute values the two event have a similar amplitude of the second phase, while peak amplitude of the first event of the Dec, 23, 2012 event is significantly larger than the other. What is similar is the sector of the path where the two phases are generated (this information derives from infrasound array processing) with the first phase of both events being produced in the uppermost portion of the channel (back-azimuth of 308-315°N) and the second phase being produced at the end of the channel (back-azimuth of 320°N). Moreover the absolute value of amplitude is different and this might be related to the dynamics of the event. The Dec 23, 2012 avalanche started as a dry avalanche in the uppermost portion of the channel and was wet in the deposition area, while the March 11, 2013 events, occurring late in the season, was a wet avalanche all along the channel. This might explain why the first phase of this event is associated with a larger amplitude. A short discussion on this point has been added in the text (Pages 11-12).

Comment: L.207 In addition to mentioning the third phase, the same type of shape 2 (in Fig 3) is also observed in Kogelnig et al, (2011). A detailed explanation of all these observations is necessary. This phase corresponds to the latter part of the infrasound signal for a specific type of avalanche. Other parts of your signals are also similar to signals presented in the mentioned paper (Kogelnig et al., 2011). Reply: The

paper Kogelnig et al . 2011 shows infrasonic waveform recorded with a single sensor from different snow avalanches that occurred in the Vallée de la Sionne test site. Different events did produce different infrasonic waveforms that are possibly related to differences in the path (page 2360 section 3.2.2 of the paper Kogelnig et al., 2011). However the authors do not provide any clear description on the mechanism producing such a waveform. Therefore we think that a detailed comparison between our waveforms and the waveforms presented in Kogelnig et al., 2011 might be misleading.

Comment: L. 213. The most probable situation is that the array detects all the energy of the existing sources, but the low energy would be masked by the high energy. As a result, the detections would correspond to the most energetic sources. Please, clarify both the sentence and the paragraph. Reply: Lines 214-216 clearly state this point.

Comment: L. 216 Please, indicate that this sentence is an explanation of the gap between the end of phase 2 and the beginning of phase 3 in Fig. 3. Reply: A detailed analysis of raw data shows that the gap is related to an increase of noise which produces an increase of the signal-to-noise ratio and thus directly affects array processing.

Comment: In addition, note that different amplitudes are observed. This perhaps is not an important point in your detection system. In such a case, if your system is independent of the type and size of the avalanches, this independence could also be a merit of your detection system: independent of the type and size of the avalanches and could also form part of the conclusions. Reply: The infrasound array processing is controlled by the frequency content of infrasound, the signal-to-noise ratio and the sensor sensitivity. The different points are discussed in several sections of the manuscript.

Comment: L.222 Add "front". Reply: The term front was added in the text.

Comment: L. 231 Explain more this sentence a little to highlight your contribution by comparing it to the usual method of detection (presented in the previous chapter). Reply: The sentence was expanded to highlight the novelty compared to the method presented already.

L. 238-239 The subindex "a4" is not necessary. Change the name for the sake of simplicity. Reply: xa4 was changed into xa to make the reading easier.

Comment: L. 246-252 Replace “mutual” by “relative”. Rewrite the entire paragraph. What does non-hogeneous azimuthal resolution of the path mean? Try to write short sentences. Reply: The paragraph was reorganized to make it clearer.

Comment: L. 261 velocity peaks? Do you mean velocity increases? Reply: The text was changed following the comment of the reviewer.

Comment: L. 263 In Fig. 5 a gap in the velocity (1:20) is observed but not in the angle. An explanation of this is necessary. Please, indicate the units of time in the figures. Reply: Infrasound is radiated by the avalanche front, propagates in the atmosphere and is recorded at the array even if propagation is not line-of-sight. This was shortly clarified in the text. Time unit in the figure is UTC (Universal time) and is written in the figures. The units of time in the figures were also corrected following the comment of the reviewer.

Comment: L. 268 Indicate units of distance Reply: Units of distance were added in the text.

Comment: L. 272-277 Please, specify the good match to which you are referring. Why do you mention these papers in this context? More detailed explanation concerning this conclusion is needed. Reply: The text was changed following the comment of the reviewer. The papers mentioned in this context provide estimation of density currents (pyroclastic flows and snow avalanches) with infrasound array analysis and are thus corroborating the presented results. The sentence was rephrased to make it clearer.

Comment: L.281-282 This sentence is not necessary. It does not correspond to this section. Reply: Following the comment of the reviewer, this sentence was removed from the text.

Comment: L. 286 Add "2013". Here the information on the filtering characteristics is

not necessary. In any case, include it in the section of data processing. Reply: The year “2013” was added in the text. Concerning the frequency band of analysis, this information is strictly related to array processing, which is usually performed in multiple frequency band. We thus prefer to keep this information in this section. Following the comment of the reviewer, the frequency band of analysis was included also in the section of data analysis of the Dec 23rd event (Section 3, Figure 3).

Comment: L. 289 Replace “recorded for” by “associated with” . Reply: The text was changed following the comment of the reviewer.

Comment: L. 289 Which is the relation between the back-azimuth and the propagation velocity to include a "while" in the sentence? Divide this into two sentences. Reply: The text was changed following the comment of the reviewer.

Comment: L.293 Is there no contradiction between this information and that of L.90? Please, clarify. Reply: Following the comment of the reviewer the text was clarified to avoid confusion.

Comment: L.306 Compare the number of detections indicated here and that of L.323 and L.286. Reply: The correct number is 31770. The mistake was correct in the text.

Comment: L.317 An explanation is needed concerning the different shapes of the avalanches, especially that of the avalanche on 2012/12/10 and the others. An explanation is also needed for the differences in the amplitude of the infrasound signals of the 2012/12/23 avalanche and that of the avalanche on 2013/03/11. In theory the 3 avalanches descended down the same couloir. Reply: The comparison of the three infrasonic signals presented in Figure 8 was developed in the text following the comments of the reviewer.

Comment: L.319. Since the only difference of the threshold criteria in this case is that the range of the back-azimuth 310_N -320_N is not considered, highlight this and eliminate the other criteria. Reply: Done in the text following the comment of the reviewer.

Comment: L. 328 Replace "which is in agreement" by "which corresponds to". Reply: Done in the text.

Comment: L. 330- 332 Rewrite the paragraph with short sentences. Reply: The paragraph was rewritten following the comment of the reviewer.

Comment: L.336 and 337 Indicate area, zone, path: : :. These are not events, you are referring to areas. Reply: We changed the text following the comment of the reviewer to make the topic clearer.

L. 346 add references and specify the type of radars. Reply: This was done in the text.

Comment: L.348 Replace “mutual” by “relative”. Reply: Done in the text.

Comment: The authors in this section must mention the different benefits or differences from the array measurements of infrasound and seismic signals. They mention seismic signals in the introduction. It is clear that there is no way of comparing these data in the Grosstal area but a comment on this is opportune. You also have to mention the contribution of ThuÌĹring et al., (2015) on infrasound detection. Reply: The discussion and conclusion section was modified according to the comment of the reviewer with the recent contribution of ThuÌĹring et al., (2015) on infrasound detection briefly described. However we prefer to avoid discussing about the differences of seismic and infrasound as seismic is included only in the introduction (as well as videogrammetry) to describe the existing monitoring system, but is not considered in the manuscript. For this reason we believe that adding a comment on seismic at this stage is more confusing than helpful.

Comment: L. 355-371 Indicate here or in previous sections the difference in the back azimuths and velocities obtained when considering an extended moving source or a punctual moving source. Please, mention that you are determining only the front velocity. Moreover, draw some conclusions in relation to the type of avalanches that the instruments used can detect. This enhances the value of the infrasound use. Reply:

The ability of in infrasound array to detect an extended source is discussed in the text (last paragraph before section 3.1). Array analysis is indeed pointing to the most energetic source and no information is available for additional sources unless acting in different frequency bands. In order to avoid confusion we delete here in the discussion and conclusions the terms “linear” and “extended”. This topic is perfectly clear to experts of array processing but it might be misleading here.

Comment: L.371-381. I would include this in the abstract. Reply: This sentence was added in the abstract as suggested by the reviewer.

Comment: In addition, add in this section some comments on the criteria mentioned in the title. Reply: This was done in the text.

Comment: L.493. Eliminate “in background” put "The profile is represented by the black dashed line”. Reply: The text was corrected following the comment of the reviewer.

Comment: L.494. “No data” is not equivalent of “decay of velocity”. Rephrase. Reply: We agree with the reviewer. The sentence was removed from the text being useless and confusing.

Comment: Figure 3. Indicate the units of time. (s?) Reply: Units of time (hh:mm) were included in the figure.

Comment: L. 499 Is there one avalanche or more than one? Reply: Detections refer to a single avalanche. The text was corrected.

Comment: Figure 5 Indicate the units of time. (s?) Reply: Units of time (hh:mm) were included in the figure.

Comment: Figure 6 Indicate the source of the data from the radar. Reply: The radar data were provided by the municipality of Ischgl. This is now stated in the acknowledgement.

Comment: Figure 8 Indicate the units of time. (s?) Reply: Units of time (hh:mm) were

included in the figure.

Comment: Is this the infrasonic signature of the array or is this an infrasound time series of one sensor? Reply: This is the data recorded by a single array element. Following the comment of the reviewer the text has been corrected.

Interactive comment on Nat. Hazards Earth Syst. Sci. Discuss., 3, 2709, 2015.