Real-time detection of natural snow avalanches by Infrasonic Array Network (IAN) on December 2012 in Valtournenche – Aosta Valley (IT)

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ABSTRACT: Since 2009 and within the Operational programme Italy-France (Alps ALCOTRA) – Projects "DynAval" (2009-2012) and "Map^3" (2012-2014), infrasonic array technology is tested in Aosta Valley to real-time detect the natural and artificial avalanche activity in the Alpine areas. In winter 2012, an Infrasonic Array Network (IAN) operates around the Monte Rosa and Matterhorn areas, monitoring ~250 km^2 of Valtournenche, Ayas and Gressoney Valleys. If single infrasonic array allows detecting small-to-medium size (~500 m^3) powder avalanches in the 3-10 km distance range, providing relative location (direction of provenience and recording time) of the source, the IAN allows more precise location (geographic position and time of occurrence), and the broadening of the area covered by the avalanche monitoring system. Information on identified events are broadcasted automatically in real-time (every 15 minutes), thus indicating potential sectors where avalanches might have occurred during the last 24 h or where to focus further avalanche control activity. The validation of the locations is done by comparing ground-truth (natural or artificial) avalanche events with the infrasonic measurements. This was possible thanks to daily data collected by the Avalanche Warning Service of Aosta Valley thanks to an excellent cooperation with snow observers, mountain guides, ski patrollers, dams operators, forest rangers, finance guards, etc… The paper presents data and analysis of natural events occurred in December 2012 in Valtournenche – AO (IT) which show how IAN is able to detect small-to-medium size avalanches in real-time also in bad weather conditions (snow storms, fog, etc …) and in not-accessible areas.

KEYWORDS: infrasonic array, snow avalanches, real-time monitoring .

1 INTRODUCTION

Monitoring of snow avalanches activity represents a crucial parameter to compare predictions and real effects.

To get the real time news on avalanche release and its geographical location is essential for risk management to start up rescue procedures (to assist injured, close roads or achieve isolated people, etc ...), but also to understand the real snow & weather conditions and local avalanche hazard. Besides, this knowledge is fundamental to understand and build risk scenarios based on geographical, morphological and snow & weather peculiarities to improve the prediction and the prevention of avalanche risk.

However, at present natural avalanche activity is mainly based on field observations, which have a limited range and are possible only during the daylight with good weather, in accessible areas.

Since 2009, to automate the avalanche detection in real-time and make it independent on meteorological and topographical conditions, the Department of Earth Sciences of University of Florence in collaboration with the Regione Valle d'Aosta is using the infrasonic array technology.

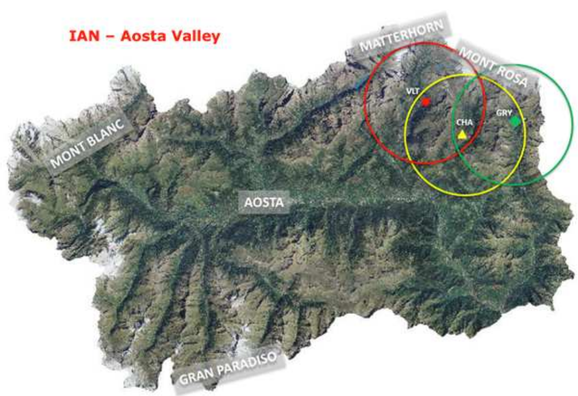

Figure 1. IAN localisation in Aosta Valley (IT) with the three infrasound arrays and their detection areas (in red one referring to Valtournenche - AO).

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The results obtained during the last 3 years indicate that small-to-medium sized snow avalanches can be detected in the short-to-medium range distance (3-10 km). Despite, a single array is not able to determine the precise source location of avalanche. In order to solve this problem, a network of 3 arrays is operating since December 2012 around the Mont Rosa and Matterhorn international ski resorts on the related massifs.
In this paper, we present the snow avalanche detection of IAN – Infrasonic Array Network, on December 2012 in Valtourneche – AO (IT).

2 INFRASONIC ARRAY NETWORK - IAN

Since Dec. 2012, an Infrasonic Array Network (IAN), consisting into 3 small-aperture array, operates around the Monte Rosa and Matterhorn ski resort areas, covering ~250 km^2 of Valtournenche, Ayas and Gressoney valleys, for real-time, automatic, detection of natural and artificial snow avalanches (Fig.1).

Figure 2. Array installation tasks in the forest (Summer 2012, Loc. Champdeleve – Valtournenche – AO, Italy). The infrasonic sensor is inside the blue box and the little yellow house contains the power and data transmission units (photo: N. Durand).

Each infrasonic array are designed by ITEM srl (www.item-geophysics.it) and consists of 4, high sensitivity (10^{-3} Pa, 0.5-50 Hz), infrasonic sensors deployed in triangular geometry and ~150 m of aperture. Data are sampled at 100 Hz and transmitted in real-time to Florence for near real-time (< 2 minutes) processing. Real-time data transmission is guarantees by UMTS technology. The array was design to require low power in order to operate with gel cell batteries and solar panels. We deployed the array in a forest (Fig. 2) and the infrasonic sensors are installed inside boxes completely covered by snow (Fig. 3) to reduce the effect of wind on the sensor (Adam et al., 1998).

Figure 3. The infrasonic sensor partially covered by snow in early winter 2012/13 (photo: G. Ulivieri).

Infrasonic array processing allows a significant increase in the signal-to-noise ratio and signal detectability, leading to identify infrasound radiated by small-to-medium size (~500 m^3) powder snow avalanches for distances up to ~10 km. Although, array processing can only provide the direction of propagation and the recording time of pressure waves traveling across the array and thus prevents unique source identification without additional available constraints. However, source ambiguity can be significantly reduced with multiple arrays, and the IAN in Valle d'Aosta was deployed in order to improve the efficiency of infrasound investigation and location of snow avalanches in the area.

Infrasound data recorded by each array of the network are analysed with suitable array processing procedures (Ulivieri et al., 2011) and, when recorded by multiple arrays, are then combined for unambiguous source location. Among the many infrasound sources detected by one array (wind, microseism, earthquakes) industrial activity, traffic), only that events which are compatible with the infrasound produced by avalanches (IAV) are provided to the Avalanche Warning Service of Aosta Valley (AWSAV) and local authorities through a dedicated web site.

The Aosta Valley IAN represents the first example of a medium-range (up to < 20 km) infrasonic monitoring system of snow avalanches, and results available point to a promising application for an efficient monitoring and research.

3 DATA SURVEY

To start the validation of IAN, since Winter 2012/13, an important (from the amount of data point of view) daily data collection was done by AWSAV. This activity coincides with the data collection of daily (MODEL 1 – AINEVA, MOD1), occasional observations and all the information on natural and artificial avalanche releases together with the artificial avalanche release device shots (i.e., Gaz-Ex®, DaisyBell® and explosives) recorded by the two ski resorts of the three monitored valleys. All the information about observed avalanches were then entered in a proper database exchanged with Department of Earth Sciences in Florence (IT) coupled with a GIS maps indicating, in UTM ED 50 reference system, the real or rough coordinates of release areas and shots. This was possible thanks to the excellent cooperation together with the AWSAV and snow observers, mountain guides, ski patrollers, dams operators, forest rangers, finance guards, etc …).

4 SNOW AVALANCHE EVENTS IN VALTOURNENCHE (AO), DEC 2012

4.1 Avalanche events of 3rd December

The early Winter in Aosta Valley led at the end of November a 90 cm thick snow cover at 2500 m asl. At the beginning of December, northern icy currents invested the Aosta Valley decreasing drastically temperatures (since 2nd Dec.) and intensifying persistent N-W winds at high altitude (> 3000 m). From the midday to midnight of 3rd Dec., the automatic weather station “Grandes Murailles” (AWS1 in Fig. 4) at 2566 m asl recorded a growth in thickness of the snowpack equal to +54 cm bringing the its total height of 134 cm. Besides, strong winds rehashed the snowpack, eroding and forming a wind crusts on the North slopes and along exposed dorsals. Important snowdrift events formed and accreted the windloads. The lack of visibility during the snowfall did not allow observing the spontaneous sluffs from the 1CGN, 1GOJ and 03GF manual stations (Fig. 4).

4.2 Avalanche events of 8th December

From the 4th to 8th Dec., a series of new snowfall deposited about +80 cm of fresh snow (data from AWS1) getting a snowpack total thickness equal to 160 cm and causing a natural sluffs from vertical rock faces around Valtournenche (from the Matterhorn to Grandes Murailles) that overloaded the related glacier at 3000 m asl.

Besides, the snowfall was accompanied by strong winds at high altitude from N-NW direction that contributed to over-load southerly and easterly aspects. The combination of snowfall and strong winds has quickly led to accumulation even with a height thicker than one meter.

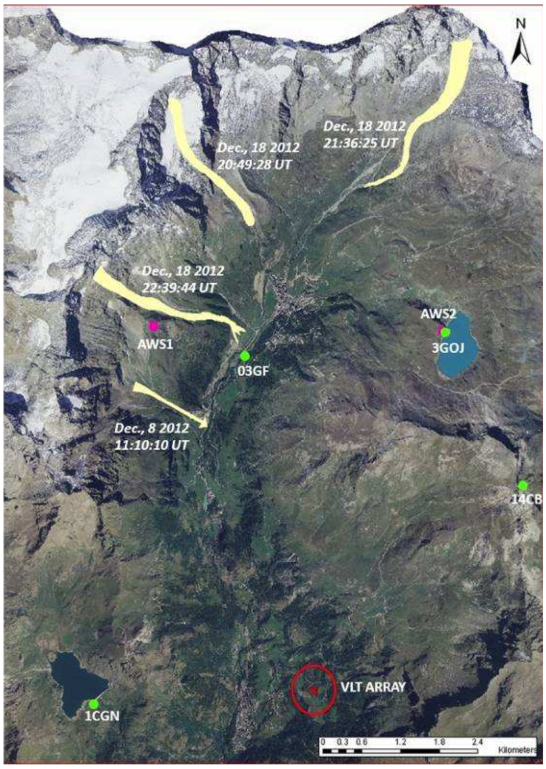

Figure 4. Map of avalanche events detected by daily observations (1CGN, 1GOJ and 03GF manual stations) in Dec., 2012 in Valtournenche – AO (IT).

Figure 5. The powder part of n. 05_010 "Tour du Créton" avalanche occurred on Saturday, 8th Dec. at ~12 am (local time) taken from Breuil-Cervinia (photo: L. Isnardi).

These conditions (thick snowpack on the ground, overloads given by fresh snow and wind) have induced big powder natural avalanches. One of these is the n. 05_010 "Tour du Créton" whose trigger occurred on 8 Dec., at around 11:10 am. It caused by the release of soft slabs on large and steep, rocky and glacial eastern slopes ranging from Mont-Rouge (3242 m) to Tour-de-Créton (3585 m) running through several rock jumps and steep and wide channels, stopping close to Marmore river at 1920 m asl (RAVA, 2013) with an estimated 400 m width deposit. The powder part of avalanche (estimated in 200 m height and 400 m width) crossed the Marmore river and the n. 46 regional road, going up the opposite slope (Fig.5).

4.3 Avalanche events of 18th December

The snowfall occurred from 13th to 18th Dec. piling up around 65 cm of the fresh snow (data from AWS1) getting a snowpack total thickness around 200 cm. Initially temperatures stayed low (around -10℃ at 2000 m asl) and then gradually rise to around -4℃. The feeble/moderate winds, confined to higher altitudes (above 2700-3000 m) from the SW or SE direction, modified the snowpack reshuffling the fresh snow, forming cornices and packing thicker (more than a couple of meters) cohesive snow layers on weaker faceted crystals layers.

Figure 6. The Matterhorn (4478 m asl) and the ridge of Fourclaz (on the right) where is located the Mont Cervin glacier. The red circle indicates the released slab (around 300 cm thickness) of n. 05-093 "Haute-Glacier du Mont Cervin" avalanche (photo: G. Torelli).

These conditions explained the intense avalanche activity recorded during the 18th Dec., from 20.45 to 22.40 pm in which three large-sized powder avalanches occurred.

At 20.49 UT (time from array, see Fig. 11c), from the upper part of Mont Tabel glacier (3580 m asl) the 05-036 "Mont Tabel" avalanche occurred. A large (150 m) slab was released from a SE side close to rocky slope, jumping down for 1200 m and triggering more slabs that fed the avalanche flux. The dense flow stopped at the avalanche dam (2390 m asl) while the powder part crossed it.

One hour later, at 21.36 UT approximately (time from ski patrol that find correspondence with the time from the array, see Fig. 11c), the n.05-093 "Haut-Glacier du Mont Cervin" avalanche was detached from Matterhorn slopes (more than 3000 m asl) stopping at the intersection of the ski runs n. 9bis and 5 of the Cervinia ski resort (Fig. 6).

At 22.39 UT (time from array, see Fig. 11c) the release of the third avalanche, the n. 05-11 "Avouil (Hotel Carrel) - Becca de Guin SE" at 3300 m asl of Grandes Murailles occurred. A large (250 m) slab jumped for 1300 m and stopped close to the Avuil village at 2000 m.

Figure 7. An image footage of n. 05_011 "Avouil (Hotel Carrel) - Becca de Guin SE" avalanche basin. On the right, the southern part of avalanche dam built to protect Breuil-Cervinia (photo: RAVA, 2013).

Due to intense snowfall and the darkling, the avalanches have been observed just only on the following day.

5 ANALYSIS OF IAN DATA – DEC 2012

The important information collected by the AWSAV during the December 2012 in the Valtournenche valley were crucial for a preliminary analysis of the IAN records. In particular, the position and time of ground-truth events were used to test infrasonic location procedures. The infrasonic and observations data moreover, have been compared to evaluate the infrasonic detection capability.

5.1 Infrasonic location

Ground-truth position of the Dec., 18 2012 big avalanche (Fig. 4) and Gaz- Ex explosions during avalanche risk management activities in Cervinia ski resort (Dec., 7 2012, Fig. 4), which were recorded at the three arrays of the network (Fig. 8a-b), were used to calibrate the location algorithms and estimates the location error.

For location analysis we compare two different algorithms mainly base on the arrival times and propagation velocity. Propagation velocity within the network was estimates using multiple array record, in particular using the explosions records which show a clear onset (Fig. 8a). In these cases the recorded arrivals time are compatible with a propagation velocities of ~320 m/s (Fig. 8, dotted, blue lines), as expected for direct wave at low temperature. Small variation from this estimate has to be considered in relation to the air temperature, humidity and wind velocity variations. Besides the infrasonic location procedures required a specific treatment, which is behind the scope of this work, in summary the first method (METHOD1) uses a grid search procedure at a fixed elevation (2500 m asl) to determine a preliminary source region rather than a single estimated source location. Once a set of arrivals has been recognized as an event at 2 or three arrays of the network, boundaries for the source region are obtained by assuming fixed limits (310-340 m/s) on sound propagation velocity of the infrasound signal. The second one (METHOD2) formulates the problem as a system of equations solved using a constant atmospheric velocity model and a least squares approach. An initial solution for use in the inversion is obtained from arrival time data at 12 stations of the network and refined through successive iterations.

First results are quite promising, indicating that the two time-based methods allows the location of a point source such as explosions with less then 500 m of error at distances between 6 and 19 km from the arrays (Fig. 8c), while larger error is expected (~1 km) for linear moving source with more complex waveform as ava-

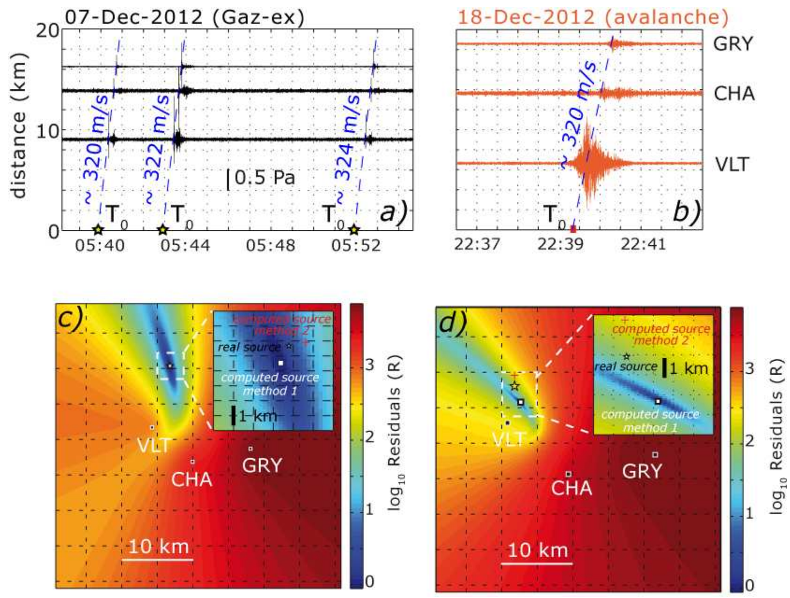

Figure 8. a) Infrasonic traces of 3 Gaz-Ex® explosions in Cervinia ski resort recorded by VLT, GRY and CHA arrays at distances between 8.8 and 16.1 km. b) Infrasonic traces of the Dec., 18 natural avalanche recorded by VLT, GRY and CHA arrays at distances between 4.8 and 19.3 km. Dotted blue lines indicate equal propagation velocities. c and d) Results of the infrasonic source location analysis given by explosion (c) and avalanche (d) triggers, using two different methods (METHOD1 and METHOD2).

lanches (Fig. 8d). Besides the quite good results, we intend to further improve the infrasound location analysis in the future by incorporating realistic topographic and back-azimuth data.

Besides the 4 avalanches share a similar dynamics, magnitude and position relative to the arrays, producing, in fact, a quite similar infrasonic amplitude, waveform and duration at the VLT array (Fig. 9b-c, orange traces) and indicating a common source dynamic, only one by 4 avalanches was recorded by at least 2 array of the network. For the three Dec., 18 avalanches also the occurrence times are very close.

plitude (0.1-0.4 Pa), duration (35-85 s) and frequency content (2.1-3.5 Hz), as well as wavefield parameters such as back-azimuth and apparent velocity migration, which are indicative of the infrasound produced by big-sized (∂h~1500 m, ~10^4 t, size-4 according to the Canadian snow avalanche size classification, McClung and Schaerer, 1980) natural avalanches with a dominant powder part at distances up to 10 km.
Based on the infrasonic signature of these verified avalanches (amplitude, duration, frequency content, etc.) we analysed the infrasonic data of the VLT array in the Dec. 1-20 period in order to extract all the possible natural avalanches oc-

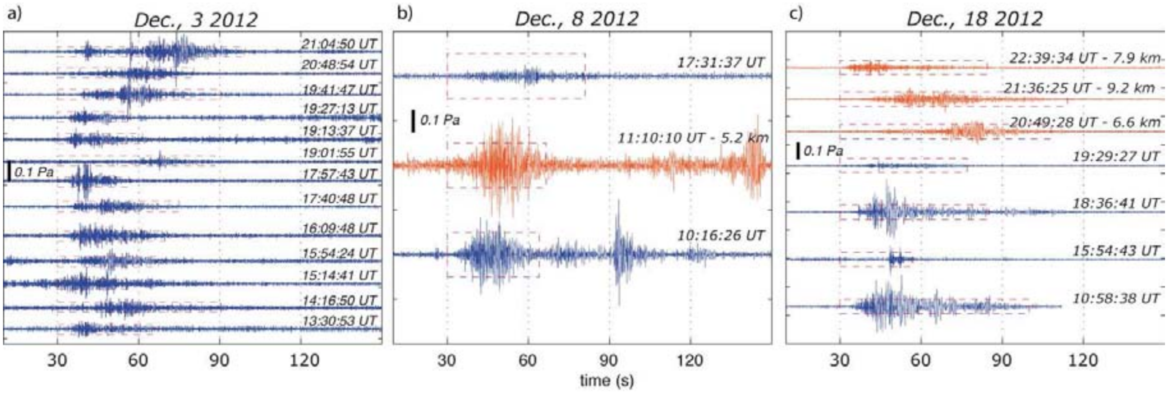

Figure 9. a) Infrasonic traces of some of the 23 IAV major events on Dec, 3. b and c) Infrasonic traces of the 3 and 7 IAV events on Dec, 3 and Dec., 18, respectively. Orange traces indicate the verified big-sized, powdered, natural avalanches.

As a consequence, the lack of records of 3 by 4 avalanches at all the arrays indicates that strong local propagation effects, mostly controlled by the extreme topography and/or wind field profile, can affect pressure wave propagation even at range of 10-20 km and most probably play an important role in the detection capability at these distances. A detailed modelling of the infrasound propagation (local scale) needs in order to evaluate the effects due to wind and topography.

5.2 Infrasonic vs avalanches monitoring activity

The 4 avalanches on Dec., 8 and 18 2012 occurred in the Valtournenche valley and verified by the AWSAV (Fig. 4), were clearly recorded by the VLT array at distances between ~5 and ~10 km (Fig. 9b-c, orange traces). These avalanches show a characteristic infrasonic am-

curred. To extend the analysis to small-to-medium sized avalanches, the amplitude threshold was reduced to 0.03 Pa. The analysis stopped on Dec., 20 2012 as problems to power supply at the VLT array caused the loss of data until Jan 2013.
Within the selected period 137 IAV events were detected by the VLT array (~6 events/day). The daily trend of IAV events (Fig. 10) shows three increasing between 3-4, 10-13 and 17-18 Dec., identifying three phases of high level of IAV activity. Although only four IAV were verified in the selected period (Fig. 9, orange traces), most of the extracted waveforms (Fig. 9, blue traces) show a quite good correlation each other and in particular with the waveforms of the documented avalanches (Fig. 9 b-c, orange traces), strong suggesting that signals being produced by natural avalanche activity.

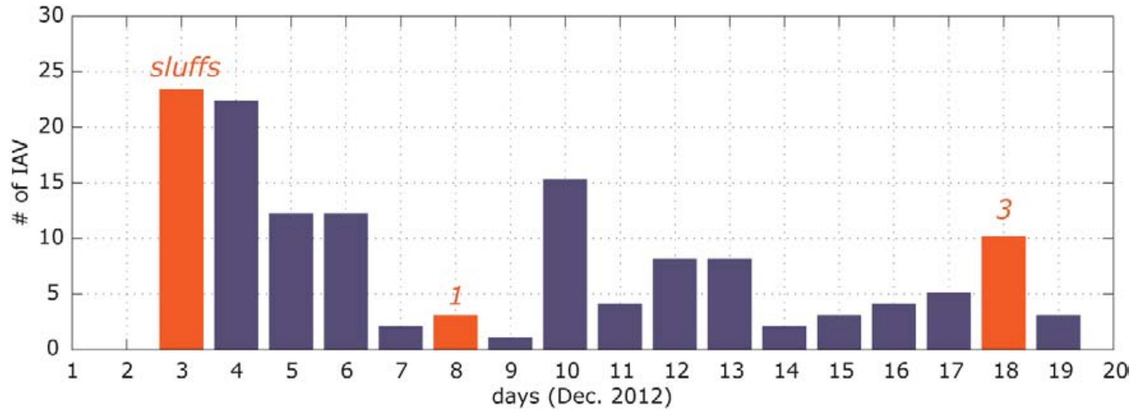

Figure 10. Daily number of IAV events. Orange colour indicates the days with verified natural avalanches and sluffs occurrence, see Fig.1 orange traces).

DAY	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
L1	0	0	0	/	/	/	/	/	/	/	1	0	0	0	0	1	/	4	1	0
L7	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	4	3	3	3	3
ADR	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3

Table 1. L1 and L7 indexes from MOD1 – AINEVA snow & weather code from 1st to 20th Dec, 2012: L1 identifies the number and size of natural avalanche occurrence (increasing from 0 to 5) while L7 the local avalanche danger estimated by avalanche guards (increasing from 1 to 5). ADR is the regional avalanche danger expected by AWSAV.

Possible natural avalanche activity was forecasted by the AWSAV in the same period, as evidenced by the 3-Considerable avalanche danger degree (L7 and ADR in Tab. 1), indicating that “the snowpack is moderately to poorly bonded on many steep slopes (> 30°)” and “triggering is possible, even from low additional loads particularly on the indicated steep slopes, in some cases medium-sized, in isolated cases large-sized, natural avalanches are possible” (Avalanche Danger Scale, www.avalanche.org). The two main phases of snowfall accumulation between 3 and 8 Dec and between 13 and 18 Dec. together with the windload events reported by the automatic station “Grandes Murailles” (AWS1 in Fig. 4) strong support the presence of natural avalanche activity in the selected period and find a quite good qualitative correlation with the IAV events detected by the VLT array.

Besides the regional and local danger degree and the bad weather that prevented observation on 8 days (L1=/), no avalanche occurrence (L1=0) was reported for the 8 by 12 days with quite good visibility. Only few small-sized natural avalanches occurrence was reported on 11, 16, 19 Dec. observation (L1=1), and few big avalanches occurrence only on 18 Dec. (L1=4). This inconsistency highlights the limits of the field observations (the visibility being strongly dependent of weather but also on orography, which limits the extent of the observation itself) and the potentiality of the infrasonic array monitoring for the observation of natural avalanche also during day night, absence of visibility and in inaccessible areas.

6 CONCLUSIONS

The multiple array records of some ground-truth events indicate that a point source such as explosions can be located with less then 500 m of error at distances between 6 and 19 km from the arrays and also for sources outside the network. Larger location error (~1 km) is expected for linear moving source as avalanches. The improvements of the location procedure would incorporate realistic topography and wind data in the analysis. Moreover, modelling propagation effects such as wind and/or local topography need in order to better assess the IAN detection capability at these distances.

During Dec., 1-20 winter period snow and weather information provided by AWSAV indicated an high probability of medium to large-sized natural avalanches occurrence in the nearby of VLT array driven by snowfall and windload events. However, classical field observations reported only few avalanches occurrence, while 137 possible infrasound avalanches were identify by VLT array, most of what compatible with the infrasound produced by 4 verified large-sized, powdered, avalanches, indicating that infrasonic array monitoring represents a powerful monitoring system that extends natural avalanche observation at wide range, during night and bad weather. Moreover, information on identified IAV events can be provided automatically in real-time, thus indicating potential sectors, or areas in the case of multiple array detection, where avalanches might have occurred during the last 24 h, hence supporting the Avalanche Warning Service of Aosta Valley in building risk scenarios.

7 ACKNOWLEDGMENTS

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