COMPARATIVE REVIEW OF INFRASOUND AVALANCHE DETECTION ALGORITHMS IN OPERATIONAL APPLICATIONS, GLACIER NATIONAL PARK, BRITISH COLUMBIA, CANADA

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ABSTRACT: The Avalanche Detection Network (ADN) is installed in Glacier National Park, British Columbia, Canada. It consists of thirteen (13) infrasound avalanche detection arrays as well as four (4) avalanche detection radars spread out along the highway corridor. Parks Canada operates the world's largest avalanche detection network. ADN has become an invaluable tool to the forecasters who are responsible for the operational avalanche risk management for the Trans-Canada Highway and the railroad within Glacier National Park as well as providing a public avalanche forecast for backcountry recreationists.

Infrasound avalanche detection arrays listen to infrasound waves (<20 Hz) which are produced by avalanches moving downhill. Each array consists of four to five sensors which are spread out in a star shape around a central cabinet. This allows the algorithm processing the received data to determine the direction of the received infrasound signal. The current algorithm processes the data of each infrasound array separately and decides if the received signal is associated to an avalanche event based on certain criteria.

A recently developed more advanced algorithm, called IDAcross, processes the data of multiple (n>1) infrasound arrays together. The anticipated benefits of this new algorithm are (1) a reduction of false alerts, (2) a higher accuracy of location information of detected avalanche events as well as (3) the detection of more natural avalanche events due to the ability to run the algorithm with lower thresholds.

This contribution presents a performance review of both, the current and the new algorithm, within the ADN over three operational winter seasons (2021-22, 2022-23 and 2023-24). The review highlights the advantages and challenges of each algorithm approach. Each algorithm has its advantages and its use for certain operational applications. The current algorithm shows detected avalanche events as a beam on the map. Whereas the new algorithm processes the received infrasound signals of multiple infrasound arrays together and allows to display a more accurate location of detected avalanche events on the map. This contribution will also explore on how the forecasters envision the operational use of both algorithms in the future.

KEYWORDS: infrasound, avalanche detection network, monitoring, algorithm.

1. INTRODUCTION

Glacier National Park (GNP) is located on the Eastern flank of a major subrange within the Columbia mountains of British Columbia Canada. Both the Trans Canada highway (TCH) and Canadian Pacific railroad (CPR) transect the GNP. Parks Canada, Avalanche control section manages and mitigates the avalanche risk posed by 134 avalanche paths in GNP through the area Rogers Pass. Both active and passive mitigation tactics are heavily relied on by ACS to ensure travelers safety through the Rogers Pass corridor.

Infrasound avalanche detection systems based on small-aperture array analysis are well suited to detect medium to large size (> 2 (OGRS 2016)) dry-snow, mixed-type and wet-snow avalanches at ~3 km range (POD 50-80%) with low (close to 0%) to medium (30%) false alert ratio (Ulivieri et al., 2011; Hendrix et al., 2018; Mayer et al., 2020).

An infrasound avalanche detection network (ADN) has been recently introduced in the Glacier National Park as tool to aid the ACS in their forecasting and mitigation strategies. ADN is a network of detections systems spanning the length of Rogers pass. Installation was completed in Fall of 2019 and consists of thirteen (13) infrasound avalanche detection arrays (IDA®) as well as four (4) avalanche detection radars (LARA, Fig. 1). ADN has become an invaluable tool to the ACS by providing information on avalanche activity trends and activity confirmation during active control measures and periods of poor visibility.

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The currently adopted IDA algorithm is based on array signal processing and a threshold-based criterion for the automatic avalanche detection. The IDA-ADN project offered the opportunity to evaluate the potential of the combined use of > 1 array analysis to improve the current algorithm performance (IDAcross algorithm). The expected improvements mainly concern a better localization of the position of avalanches and a better reliability of the detections, i.e. a reduction in the probability of false alerts.

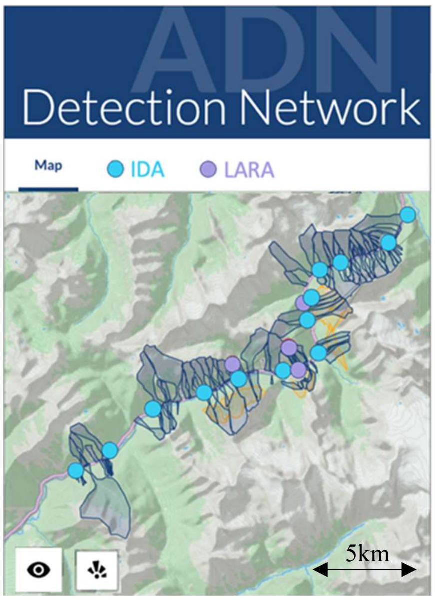

Fig. 1. Map of the Roger Pass (BC) Avalanche Detection Network (n.4 LARA and n.13 IDA) and the n.114 avalanche paths in GNP (transparent blue polygons).

The aim of this preliminary work is to evaluate the performance of the new algorithm applied to the 11 pairs of arrays and to highlight its advantages and limitations for operational purposes.

2. METHOD

2.1 IDA-ADN

Infrasound refers to sound waves with frequencies below the range of human hearing, specifically those below 20 Hz. Avalanches running downhill produce infrasound waves. While humans generally cannot hear these low-frequency sounds, they can still be detected with specially tuned sensor arrays. N. 13 infrasound sensor arrays have been installed throughout GNP spanning from the western most location at the Parks west boundary and spanning east for approximately 30 km (Fig. 1). Maximum space between sensor is approximately 3.1 km while the minimum is 1.3 km with an average spacing of 2.5 km. 121 of the 134 avalanche paths threatening TCH and CPR are monitored by infrasound arrays. Each array is installed valley bottom adjacent to the TCH in forested terrain.

An infrasound array (IDA®, Fig. 1 cyan circles) is comprised of 5 sensors designed to detect the variance in air pressure caused by infrasound waves. 4 sensors are located radially and connected via communication and power cable at approximately 100 m from a fifth sensor housed in the central component cabinet. The central cabinet contains remote power supply (solar and fuel cell), fuel, battery bank, control unit and communication components.

Raw sensor data is recorded and transmitted via the mobile network to cloud-based servers where the signal is processed through the IDA algorithm.

2.2 IDA algorithm

The IDA algorithm consists of n.2 main modules (Module 1 and Module 2).

Module 1 is the classical array signal processing (Ulivieri et al. 2011) which allows to discriminate signals from noise and, in presence of signal, to calculates the signal's wave parameters among which the direction of provenience (back-azimuth, °N respect to the array position) and the apparent velocity (or elevation respect to the array altitude, m/s). Module 1 includes n.2 different array signal processing which are dedicated to the detections of i) long-lasting, emergent signals (e.g. avalanches, Module 1-Av) and ii) short-lasting, impulsive signals such as the ones produced by explosives during avalanche control (e.g. Wyssen tower, Gazex, artillery, Module 1-Ex). Module 1 provides n.2 datasets of raw detection (Av) and relative wave parameters every 0.2 seconds.

Module 2 is the avalanche's detection criterion that aims to identify avalanche signals and discard other kinds of signals (traffic, airplanes, ...).

Once Module 2 recognizes the infrasound signal as compatible with an avalanche event, the server will initiate alerting protocols via communication paths (SMS, email and push notifications). The event information is stored and visualized in the WAC.3 web-based software.

The current operational algorithm (IDA) and the recently developed algorithm (IDAcross) differ on Module 2, i.e. on the recognition criterion of the infrasound produced by avalanches.

2.3 Module 2 - single array criterion

The single array criterion considers only the raw detections produced from a single infrasound array and does not consider the raw detections coming from neighboring arrays.

The criterion first applies a temporal clustering function to the Module 1-Av raw detections to identify an infrasound event. Then a threshold-based criterion, based on a minimum peak amplitude and duration of the event and the time trends of the back-azimuth and apparent velocity, is used to identify downward moving sources compatible with the one produced by avalanches running downhill and filter-out non-compatible ones (Ulivieri et al., 2010; Marchetti et al., 2015). This criterion also uses Module 1-Ex raw detections which allows a temporary reduction of the thresholds thus increasing the probability to detect signals of shorter duration and amplitude such as the ones produced by smaller sized, further away avalanches. This feature also allows to classify avalanches as controlled (Cav) or natural (Nav).

The Module 1 output consist of i) the occurrence time (recording time), duration and amplitude of the event (as recorded at the array), and ii) the azimuthal location on map, the latter consisting of a triangular beam with one vertex on the array position and the other two correspond to the 2 points placed at a fixed distance from the first vertex (~3 km) and with azimuth corresponding to the initial and final back-azimuth of the event (cyan patches on Fig. 2).

In terms of location, this beam can span across adjoining avalanche paths and leaves a high level of uncertainty.

2.4 Module 2 - multi-array criterion (IDAcross)

The newly developed IDAcross criterion considers raw detections (only Module 1-Av) at multiple arrays with the aim to precisely locate the signal source position.

Basically, assuming a fixed sound velocity, the criterion calculates the theoretical travel-times/back-azimuths values between a 3D grid and the array positions. The criterion then compares the theoretical travel-times/back-azimuths with the measured ones at the n > 1 arrays (Fig. 3 gray circles) to provide the IDAcross raw detections dataset (Fig. 3 blue circles).

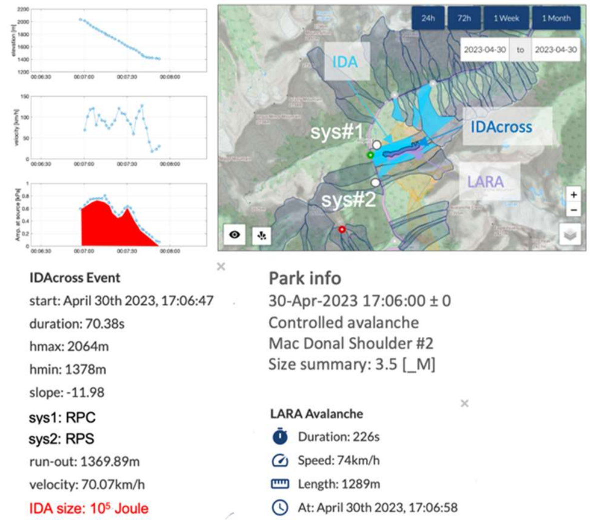

Fig. 2. Example of a size 3.5 controlled avalanche occurred on Apr. 30th 2023 in the Roger Pass corridor as detected by i) radar (LARA), ii) infrasound (IDA algorithm) and iii) infrasound (IDAcross algorithm).

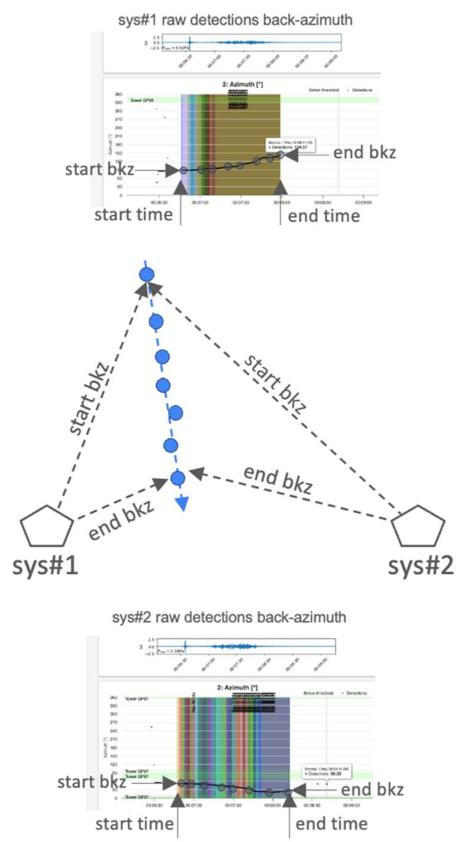

Fig. 3. Schematic representation of the IDAcross criterion.

A spatial-temporal clustering function is finally applied to the IDAcross raw detections to identify and locate the infrasound event.

The IDAcross event output consists of a polygon on a map (Fig. 2 blue polygon). The 3D position of the group of IDAcross raw detections identifying each event (Fig. 3 blue circles) are used to calculate the time trends of i) amplitude (at source), ii) elevation and velocity and (Fig. 3 upper left graphs) which allow for the estimates of the infrasound event parameters such as:

- Source Amplitude (kPa) / Energy (Joule)
- Avalanche length (m)
- Average front velocity (km/h)

The comparison of such estimates with the one provided by the radar (IDAcross Event and LARA Avalanche info on Fig. 2) highlight that the IDAcross criterion, in addition to a precise path location, also offers the opportunity of a reliable estimate of the dynamic parameters of avalanches.

Given the 3D event location, a more robust and easy discrimination between irrelevant infrasound signals (e.g. road-rail traffic, mines activities also at 30 km range, avalanche activity in opposite valleys…) and the short-range infrasound located on avalanche paths of interest is expected.

On the other hand, limitations of the IDAcross criterion for sources externally and at the borders to the system pairs (larger localization error) and in particular for large distances between pairs (lower probability of a sufficient signal duration at both systems pair) are expected. Both criteria have the distance between the source (avalanches) and the receiver (IDA array) as their main limit, but the multi-array criterion is more affected by this factor.

3. IDAcross PERFORMANCE ANALYSIS

In this preliminary study, the performance of the new IDAcross criterion compared to the one currently in operation has been evaluated in terms of Probability Of Detection (POD), which includes avalanche observations by the ACS in n.100 (out of 121) relevant avalanche paths within the GNP (Fig. 4) during the last n.3 winter seasons (2021-2022, 2022-2023 and 2023-2024). POD score is the ratio between the n. of true positive detections and the n. of observations, and it is indicative of the capability to detects avalanches of the n. 11 pairs of current IDA systems network.

The whole avalanche observation dataset consists of 2073 records of 5 > size > 0 avalanches, either natural (Na) or controlled (Xa) (Fig. 4 top).

The IDA and IDAcross detection datasets have been selected using threshold-based and spatially based filters respectively; therefore, excluding the detections not compatible with the total n.121 relevant avalanche paths of the GNP. The resulting datasets (Fig. 4 middle and bottom and Table 1) include, the true positive events related to avalanche observations and false positive events related to possible false alerts, additional true positive related to observations with uncertain time of occurrence and possible real avalanches not observed by Park Canada. The IDA dataset also includes the multiple detections of a single avalanche by more than 1 IDA system. Therefore, the detections datasets have a larger number than the observation one.

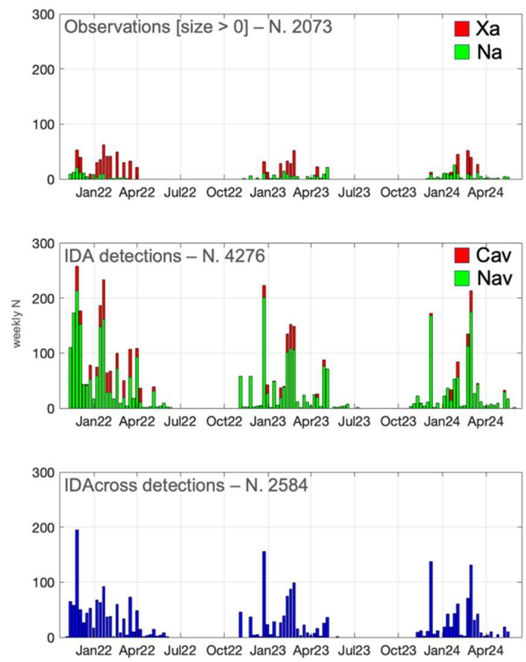

Fig. 4. Weekly number N of (top) avalanche observations [size > 0], (middle) IDA and (bottom) IDAcross detections in the Nov. 1st 2021 – Jun. 1st 2024 time interval.

For the POD computation the observations dataset has been filtered for:

- size > 2 (OGRS 2016)
- precise time of observation
- time interval with not operating IDA

resulting in a n. 1102 observations (Table 1) on n.84 different avalanche paths.

Size > 2 filter is considered as the lower limit for the infrasound methodology to reliably detect avalanches at < 3 km range (Hendrix et al., 2018; Mayer et al., 2020). In this preliminary phase of the study, the choice to use only observations with certain time was made to facilitate the cross-referencing of datasets through a semi-automatic procedure that considers both the time of observation and the position of the avalanche.

Table 1. Datasets used for POD score analysis [n.3 winter season 2021-2024]. * Only with precise observation time. ** threshold-based filtered. *** spatially filtered on n. 114 Park avalanche paths.

dataset	Tot	Xa	Na
Observations [Park Canada*]	1102	666	436
Detections [IDA**]	4276	771	3505
Detections [IDAcross***]	2584		

The overall POD scores of the two criteria are shown in Table 2 as a function of size. Single-array criterion (IDA) performs better than multi-array one (IDAcross) for all avalanche size up to size 4. As expected, as the avalanche size increases, the POD scores of both criteria increase and the difference between the two decreases.

Table 2. POD scores of IDA and IDAcross algorithms by avalanche size (OGRS 2016).

	POD [%]			
size	>2	>2.5	>3	>3.5
Nobs	1102	704	164	20
IDA	68	77	88	100
IDAcross	51	62	80	100

To better understand the meaning of the overall POD results, the POD scores for each avalanche path has been computed (Fig. 5 and Fig. 6). For a statistically significant purpose, the path-specific POD analysis considers only the avalanche paths with n > 2 observations (52 out of 84).

This paths-specific POD highlights different performances over different paths (Fig. 5). The currently operating criterion (IDA) performs better respect to the new one (IDAcross) on 51% of the paths ($POD_{IDA} – POD_{IDAcross} > 20\%$), it has similar POD scores on 42% ($POD_{IDA} – POD_{IDAcross} < \pm 20\%$), and worse POD score on only 7% ($POD_{IDA} – POD_{IDAcross} < -20\%$) of the considered paths (Fig. 6).

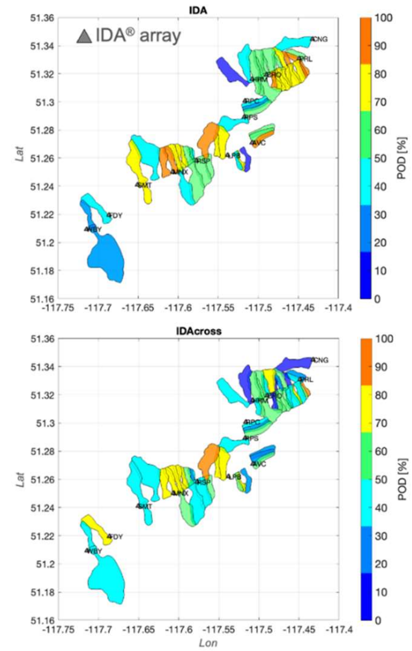

Fig. 5. Map of the POD scores [size > 2] over n.59 different avalanche paths [n. observations > 2] of IDA (top) and IDAcross (bottom) algorithms.

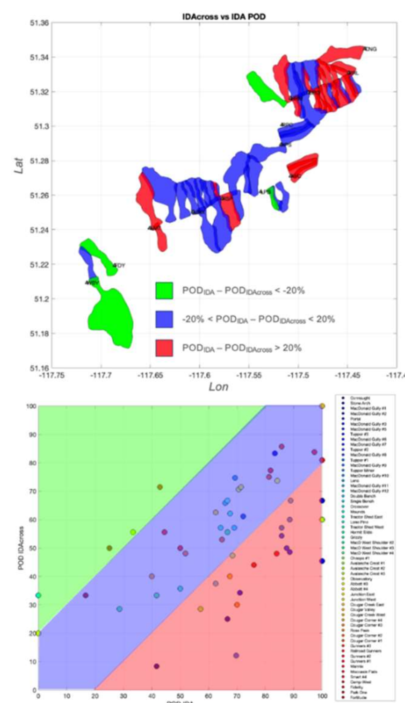

Fig. 6. IDA vs IDAcross algorithms POD scores [size > 2] over n.59 different avalanche paths [n. observations > 2] on GNP.

DISCUSSION

The multi-array criterion (IDAcross) showed very good performance in terms of precise localization (error <100 m) as well as estimation of dynamic parameters (average front velocity, run-out distance and size) of large avalanches (size 3.5, Fig. 2) at an inter-array pair spacing of ~1.3 km (RPS-RPC in Fig. 5). Further specific studies are needed (e.g. on test site) to better understand the reliability and limitations of infrasonic measurements for the estimation of avalanche dynamic parameters.

Preliminary results of the IDAcross performances in terms of probability of detection (POD) of avalanches in the 2.5-4.5 size range showed an overall lower score (POD 51%) compared to the currently operating IDA criterion (POD ~68%) (Table 2).

The worst overall performances are associated with a large variability depending on the avalanche path (Fig. 5 and Fig. 6). 51% of the avalanche paths show similar POD scores of the two criteria, 42% significantly lower IDAcross algorithm scores and 7% where IDAcross scores are better than IDA algorithm.

It is highlighted that most of the avalanche paths where the performances of the IDAcross criterion are significantly worse than the IDA criterion are relevant to the CRO-PRL array pair (Fig. 6) that has the maximum inter distance of 3.1 km, demonstrating that the distance between the array pair is one of the limits of the method itself. To better investigates the very low POD scores of the IDAcross criterion on 42% of the avalanche paths, a more detailed analysis is necessary in order to discriminate whether this limit is to be attributed to the distance between the array pairs (limit of the method due to the network density) and/or to the morphological characteristics of the path (intrinsic limit due to the avalanche dynamics).

On the other hand, the better performances of the muti-array criterion are mainly observed in the WBY-FDY array pair (2.3 km distant) and related avalanche paths in the westernmost part of the corridor (Fig. 6) where avalanche control by means of artillery is not carried out. The fact the singl-array criterion on WBY and FDY arrays runs without the avalanche control verification module (Module 1-Ex) suggest the overall lower performances of the multi-array criterion are also to attribute to this specific feature of the single-array criterion that allows for an effective reduction of the thresholds and therefore an increment of the performances in terms of detection capability of signals of lower amplitude and duration. The comparison between the two criterion on this pair hence indicates that for an interdistance of 2.3 km the multi-array criterion performs better than the single-array one in terms of capabilty to detect natural avalanche activity.

The multi-array analysis also highlighted in some cases localization errors greater than 100 m (Fig. 7). Although the interdistance between the HRM-CRO array pairs is optimal (1.3 km), such error could be attributed to i) possible distortion effects of the acoustic wave field (channeling, diffraction...) due to topography or ii) to the plane wave assumption of Module 1 of the algorithm (Ulivieri et al., 2010). Further investigations in this regard are also necessary.

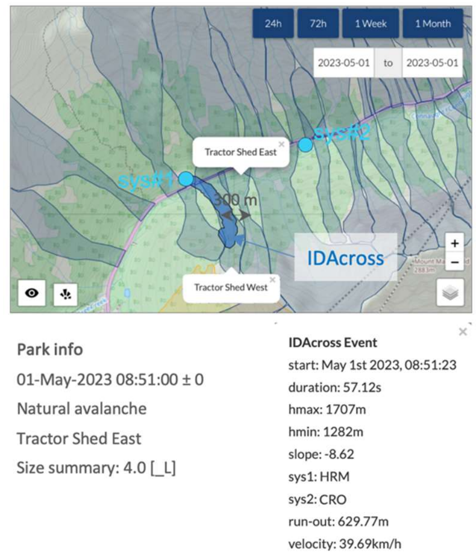

Fig. 7. Example of IDAcross path location error. The natural avalanche was observed by Park team on Tractor Shed East path while the IDAcross location indicates Tractor Shed West as path, resulting in an average location error of ~300m.

Finally, to better compare the performances of the two criteria, an analysis of the probability of false alerts in addition to the POD is necessary. In this regard, an example of possible false alerts related to long-range infrasound produced by the climax eruption of Tonga volcano (Matoza et al., 2022) located at ~12,000 km away from the GNP (Fig. 8) is reported. This long-lasting signal (hours) propagating worldwide triggered 92 false detections in one hour by the single-array criterion and no detections by the multi-array one, strongly evidencing the capability of the IDAcross criterion into reduce the probability of false alerts compared to the single-array criterion (13-30% in Switzerland Mayer et al., 2020; 0-10% in Roger Pass Hendrix et al., 2018) and hence improving the reliability of the infrasound detections of avalanches methodology.

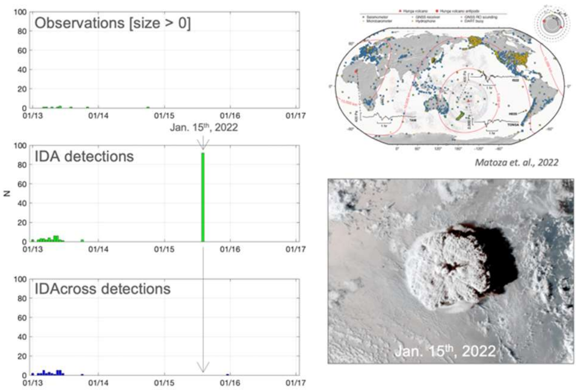

Fig. 8. Hourly number N of (top) avalanche observations [size > 0], (middle) IDA and (bottom) IDAcross detections in the Jan. 13th – 17th 2022 time interval. The peak of 92 IDA detections in 1 hour of the on Jan. 15th corresponds to a sequence of false avalanche detections due to long-range (~10000 km) infrasound produced by the climax eruption of Tonga volcano. The IDAcross algorithm, instead, filters out these detections because they are not localized on avalanche paths.

4. CONCLUSIONS

The IDA technology of the Avalanche Detections Network (IDA-ADN) operating in the Glacier National Park (BC) since 2019 has become an invaluable tool to the Avalanche Control Section (ACS).

The overall performance of the current IDA algorithm, which is based on single-array criterion, are considered appropriate (probability of detection 50-80% - probability of non-detection 95-100% - false alert ratio 0-10% of size>2 dry-snow, mixed-type and wet-snow avalanches at <3 km range, Park Canada reports) to provide near-real-time, automatic information on avalanche activity trends and confirmation during active control measures particularly during periods of poor visibility.

The n.13 IDA arrays cover ~30 km of the GNP with an average spacing of 2.5 km (1.3-2.5 km range). Several avalanches are detected at more than 1 array indicating the use of multi-array analysis as a possible criterion for more accurate detection and triangulation of avalanche events (Hendrikx et al., 2018).

The multi-array algorithm has been recently developed (IDAcross criterion) and the results of its performances in respect to the current IDA criterion have been presented and discussed.

Preliminary results are promising and have allowed to identify the main advantages as well as the limitations of the criterion.

IDAcross revealed a promising criterion to precisely locate avalanches (<100 m error) as well as to better estimates dynamic parameters such as size, run-out distance and average front velocity comparable to the independent radar measurements. However, good performance in this regard is strictly dependent on the avalanche size and/or the distance between IDA system pair.

In term of probability of detection (POD), which has been computed on a dataset of n. 1102 observed avalanches with 2.5 < size < 4.5 over n.3 winter seasons (Park Canada dataset), the IDAcross criterion showed lower overall performance (POD 51%) than the IDA (POD 68%). Paths-specific analysis revealed a wide variability of the POD score over different avalanche paths (n. 84) with performance of the IDAcross versus IDA criterion ranging from significantly worse to similar up to better.

The criterion adopted only by the IDA algorithm for the detection of signals produced by explosions affects the lower performances of the multi-array criterion during avalanche control. On the other hand, similar or even better performances of the multi-array criterion are observed during natural avalanche activity. The worse performances of IDAcross criterion, however, are due to the distance between the array pairs, since the multi-array approach needs to record enough signal to n > 1 systems. Although further and more detailed analysis is needed, the evidence indicates that the optimal range of the multi-array criterion is smaller than that of the single-array criterion. The systems pair distance limitation also affects the localization accuracy.

In terms of probability of non-detection and false alarm ratio, no specific statistical analyses have been performed yet. However, evidence indicates that the IDAcross criterion is more effective in this regard than the single-array criterion, thus offering the advantage of improving detection reliability.

ACKNOWLEDGEMENT

The authors would like to thank Beni Meier, Marc Cossette and Lisa Dreier (Wyssen Avalanche Control) for continued support in improving ADN.

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