D-SCALE VERSUS INFRASOUND: REMOTE QUANTIFICATION OF AVALANCHE SIZE

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ABSTRACT:

Infrasound monitoring is an established technology for detecting and mapping the progression of both triggered and natural snow avalanches and has been shown to be particularly effective in Little Cottonwood Canyon (LCC) in Utah, USA. This empirical study makes use of an ensemble of hundreds of triggered dry avalanches occurring in LCC, starting in 2023, to understand the relationship between infrasonic intensity and frequency content, infrasonic signal duration, and avalanche size. Specifically, we compare size estimates, using forecaster's determination of Avalanche Destructive Force (D-Scale) to develop a scaling relationship, which accounts for distance from avalanche source to infrasound sensor location. This regression permits avalanche infrasound intensity, and signal duration, to then be used for remote quantification of avalanche size during periods of time when infrasound is collected, but direct visual observations are not possible. Furthermore, we are able to discuss the advisable maximum distances for infrasound sensor deployments in order to capture avalanches of size D1, D2, and D3.

KEYWORDS: avalanche monitoring, infrasound, D-Scale, size estimation

1. INTRODUCTION

Snow avalanches produce intense low frequency sounds called infrasound, which can be recorded with specialized microphones (e.g., Bedard et al., 1988). Infrasound monitoring is particularly useful for automated detection and location of events given that visible observations are not needed. Infrasound monitoring in Little Cottonwood Canyon (LCC), Utah has been operational with demonstrated utility since 2006 (Vyas et al., 2009; Yount, 2008). Recent improvements in hardware, telemetry and signal processing techniques led by the Boise State University infrasound group in conjunction with industry Partner Snowbound Solutions (https://snowboundsolutions.com) have increased the functionality of infrasound monitoring in the last decade (e.g., Johnson et al., 2021a; Johnson et al., 2023; Johnson et al., 2024). Along with detection and location of avalanches the remote quantification of avalanche size, using infrasound, is a current objective.

This presentation attempts to relate the avalanche Destructive Scale (D-scale) metric to radiated avalanche infrasound energy. The D-scale ranges from D1 to D5 and is commonly used in North America to quantify avalanche size. In brief, the size of D-scale events is related to length and depth of deposits. The following is modified from https://avalanche.org/avalanche-encyclopedia/avalanche/avalanche-problems/avalanche-size/destructive-force-d-scale/

-D1 (20-m length; less than 1 m deep)
-D2 (100-m length; ~2 m deep)
-D3 (1-km length; 2-3 m deep)
-D4 (2-km length; 4 m deep)
-D5 (3-km length; 8 m deep)

2. CATALOG OF OBSERVATIONS

Utah Department of Transportation (UDOT) forecasters performing mitigation work along Utah State Route 210 (SR-210) attempt to quantify avalanche size in 0.5 increments and base their assessments on visual and audio verification. During mitigation work in the mid-canyon (Figure 1) a crew is usually present and able to verify if a detonation successfully triggered an event. Determination of size can be subjective especially when visibility to the slide paths is compromised or when multiple avalanches occur near simultaneously. This is a compelling reason for why infrasonic quantification of avalanche size is seen as a potentially useful, complementary tool.

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Figure 1 – Google Earth view of the Utah SR-210 corridor in Little Cottonwood Canyon with ski areas Alta and Snowbird on the upper right section of terrain. The "mid-canyon" area is monitored by infrasound sites at LCC1, 2, and 3. Data presented here from 2022-2023 come from LCC2 and LCC3 separated by approximately 500 m.

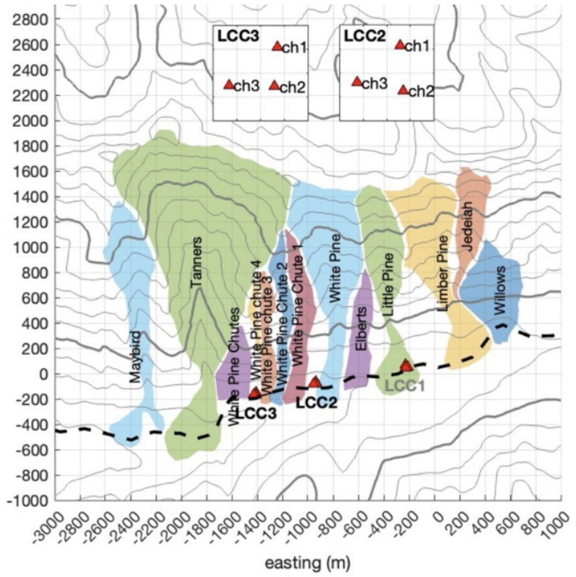

Figure 2 – map showing named mid-canyon slide paths relative to infrasound arrays at LCC2, LCC3, and SR-210 indicated with dashed line. Contours are drawn at 100 m intervals.

This study reports on data collected during the 2022-2023 season when 683 (mostly triggered) avalanches were documented in the UDOT operational catalog. Forecasters working to clear hazardous snow conditions from starting zones in the mid-canyon slide paths primarily used artillery from a 105-mm howitzer to trigger avalanches. In total 190 avalanches triggered by howitzers were reported in the mid-canyon in the catalog and 8 were triggered by charges. Additionally, 31 natural avalanches were reported in the forecasters' catalog for the Table 1 slide paths.

Path name	#	Location	# natural	#road-hit
Maybird	16	West	3	4
Tanners	8	West	3	2
chute #1	17	North	3	4
chute #2	26	North	8	4
chute #3	20	North	3	7
chute #4	17	North	4	4
White Pine	53	East	7	3
Little Pine	44	East	4	6
Limber Pine	10	East	0	0
Jedediah	7	East	3	1
Willows	11	East	3	2
Totals	**229**		**31**	**37**

Table 1 – summary of 2022-2023 avalanches occurring in the UDOT operations catalog in LCC's mid-canyon. Second column corresponds to total events in catalog. This number includes a number of natural avalanches that were documented and indicated in column #4.

Of the 229 mid-canyon avalanches in the 2022-2023 catalog 223 were assigned Destructive Scale (D-Scale indices) by the forecasting team (figure 3). These numeric values correspond to estimates of avalanche size using first hand observation of the avalanches and/or the volume of deposits left behind.

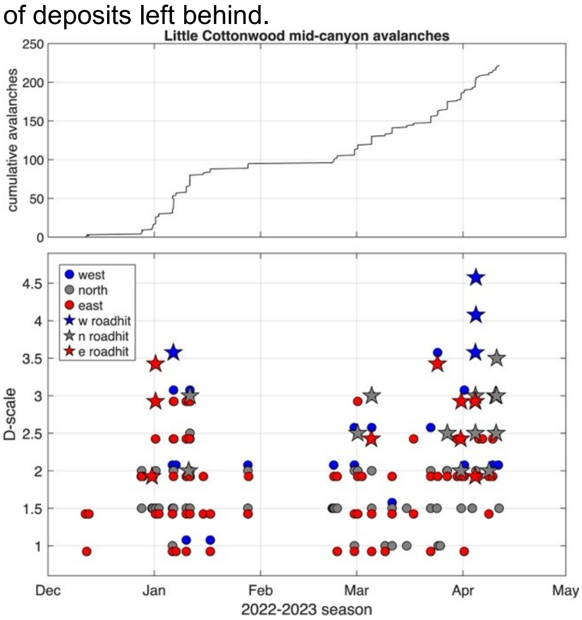

Figure 3 – chronology of mid-canyon avalanches included in the UDOT catalog classified according to whether avalanches were west of the two arrays, east of the two arrays or north (in-network). These are all events listed in Table #1. Avalanches hitting the road are indicated with star symbols

3. DEPLOYMENT GEOMETRY AND DATA

Infrasound monitoring in mid-canyon of LCC is accomplished using three arrays each with three infrasonic microphones. The arrays are located just north of SR-210 and separated by approximately 1.3 km. Data used in this analysis is restricted to LCC2 and LCC3 because LCC1 was off line in the later half of the season during an intense storm cycle in late March and April. The two three-element arrays consist of infraBSU infrasonic microphones with a sensitivity down to 0.1 Hz and sampling at 100 Hz. Because avalanche signal-to-noise is highest above about 2 Hz a 2-pole highpass filter with 2 Hz corner has been applied to the data. At the high end, the avalanche signals are limited by the Nyquist frequency at 50 Hz, with anti-aliasing filter high cut beginning practically at about 45 Hz. An acoustic energy proxy is then calculated as time integrated power over an event's duration, i.e.

$$E_D = \sum_{n=t_0}^{t_1} \frac{2 \times p[n]^2}{100} \, (Equation\ 1)$$

Where $p[n]$ is the filtered pressure time series, t_0 and t_1 are the signal start and end times and the sample rate is 100 Hz. A coefficient of two is included to consider the influence of equipartitioning, accounting for both kinetic and potential energies. Units in Equation 1 are calculated in $Pa^2 \cdot s$ and it is important to note that this is a time integrated acoustic *intensity*. While it is theoretically possible to convert this energy density to an energy in Joules [e.g., Johnson et al., 2021b], that calculation requires understanding of source-to-receiver distance, radiation patterns, and impacts of overlying snowpack on recorded pressure amplitudes. For a simple acoustic source radiating into a hemisphere the energy can be calculated as energy density integrated over a surface, e.g.,

$$E = A \times 2\pi r^2 \frac{E_D}{\rho c} \, (Equation\ 2)$$

Where *A* is a site correction factor due to snowpack, *r* is the distance from source-to-receiver and ρc is the impedance of the atmosphere, a product of atmospheric density and sound speed. In practicality, the avalanche acoustic source is neither a volumetric source nor is it compact (see discussion in Johnson et al., 2021b) so the absolute energy calculation is a nontrivial exercise. Given the uncertainties in energy calculation assumptions, including complex distributed source region and topographic complications we start by exploring the relationship between D-scale and infrasonic radiation using Equation 1 and then later try to understand the dependence upon distance.

A few examples of avalanche waveforms along with infrasound signal and energy proxy calculations are provided in Figure 4. These represent mid-canyon avalanches, which were observed by forecasters and assigned D-scales. The correspondence between catalogued event and the displayed infrasound is based upon the temporal coincidence, however there are some incidences where multiple snow avalanches are occurring in close succession (within minutes) and association of D-scale with a specific infrasonic event may be improperly attributed.

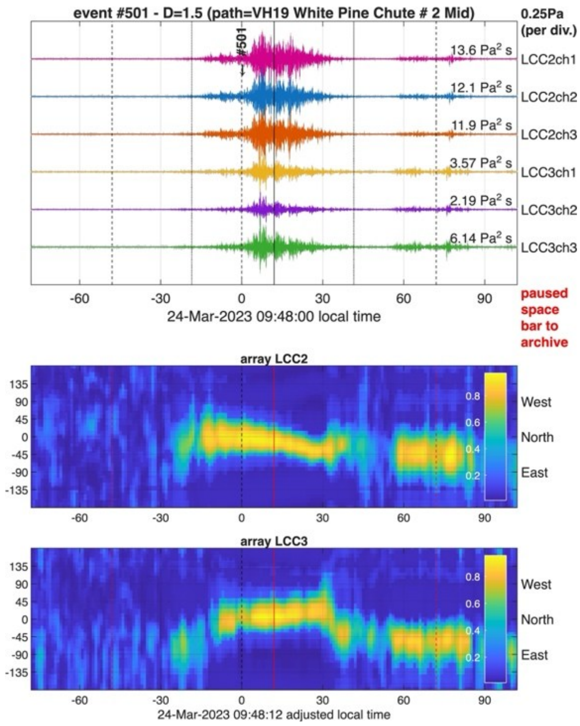

Figure 4a – An avalanche in mid-canyon that was ascribed a D-scale of 1.5. by UDOT. (top) Six waveforms from LCC2 and LCC3 are displayed with respective energy proxies in units of Pa^2s. (middle and bottom panels) Azimuthal chronologies of the avalanche over time. The back azimuth pots point to a moving source originating from White Pine Chute #2. The intensity of the colormaps is an indication of the signal-to-noise quality of the recorded avalanche. Captions for Figures 4b-d, featuring other events, are the same as for this panel.

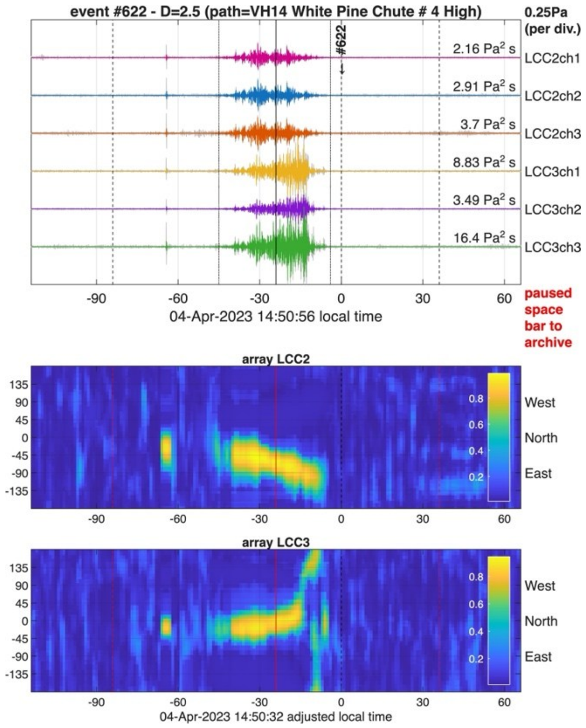

Figure 4b – An avalanche in mid-canyon assigned a D-scale of 2.5. by UDOT. These back azimuths point to a moving source originating from White Pine Chute #4. Although this avalanche was labeled much larger than the example in 4a its infrasonic energy proxy is comparable.

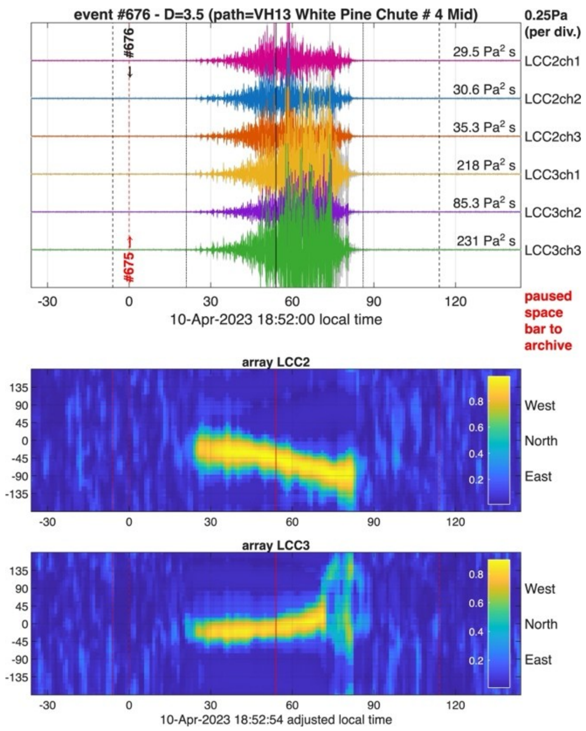

Figure 4c – A large avalanche in mid-canyon assigned a D-scale of 3.5. by UDOT. These back azimuths point to a moving source originating from White Pine Chute #4. This avalanche reached the road.

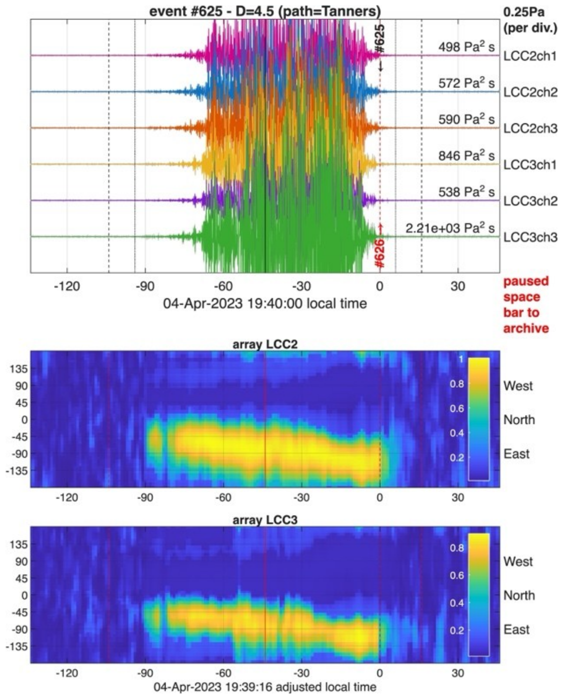

Figure 4d – A very large avalanche in mid-canyon assigned a D-scale of 4.5. by UDOT. These back azimuths point to a moving source from Tanners Slide Path, which hit SR-210 (see photo in Figure 5).

4. RESULTS

Examination of waveforms along with their estimated D-scale is essential for developing infrasound energy proxies as a means to remotely quantify avalanche size. Qualitatively there is a correlation between the two parameters and “larger avalanches appear to generate more sound”. For instance, the very large D=4.5 avalanche from Tanners on April 4th, 2023 (Figure 5) produced the most energetic infrasound signals of the season with integrated power exceeding 500 Pa^2s across the network. Notably, its quantified energies are different on some of the sensors, which is potentially due to variable amounts of snowpack covering (and muffling) the infrasonic microphones. LCC3ch3, for instance, seems to record higher intensity infrasound for all events, from March 24 to April 10, suggesting that it was perhaps relatively unburied at its site.

Examination of an ensemble catalog of infrasound statistics compared to D-scale is particularly illuminating. Figure 6 shows data from a 26-day period for which a collection of 81 events were in the forecaster’s catalog. This number may be compared with 121 avalanche events that were picked agnostically using an infrasound detection system modified from Snowbound Solutions LLC’s algorithm [e.g., Johnson et al., 2023; Ofekeze et al., 2026]. We note that it is unsurprising that additional avalanches were picked using infrasound since most of the forecasters’ surveillance is done during daytime operations.

Figure 5 – view of Maybird and Tanners in lower mid-canyon after the spring 2023 storm cycle when SR2-10 was hit by multiple large avalanches. Photo courtesy of UDOT. These two slide paths are to the west of arrays LCC2 and LCC3.

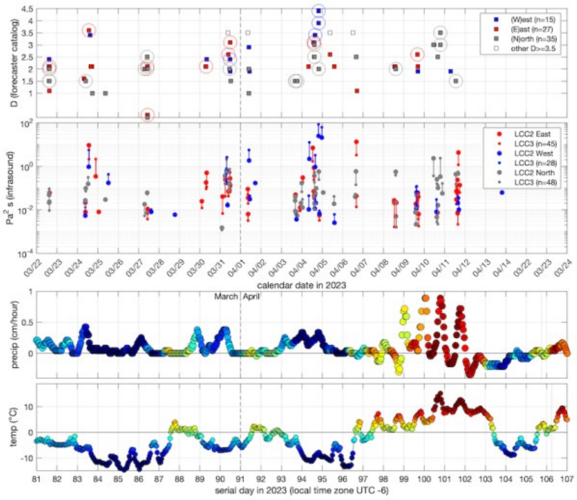

Figure 6 – a 26-day period of avalanche activity in the mid canyon of LCC in March and April 2023. Top panel shows D-scale values provided by forecasters. Circled events were autonomously identified by the infrasound picker, which found 121 events during the same period shown in the second panel from top. Bottom two panels show precipitation and temperature records from a nearby Snotel site.

5. DISCUSSION

In many cases the calculated energy proxy is greater for one array versus another. For example, the D=3.5 event occurring on April 10 (Figure 4c) was recorded with substantially greater amplitudes at LCC3 compared to LCC2. We consider that this is likely due to the fact that White Pine Chute #4 is closer to LCC3 than to LCC2 and its runout traveled along a trajectory adjacent to the LCC3 infrasound array site.

It should be expected that infrasound intensities recorded at one array may appear preferentially more powerful if that array is closer to the avalanche. This can be seen in Figure 7 where energy proxies are compared at LCC2 and LCC3 for an ensemble of avalanches. For avalanches located to the West of the two arrays LCC3 shows systematically larger energies, whereas the opposite is true for avalanches east of the two arrays. In this case, energy is greater on LCC2. It is both evident and intuitive that distance plays an important role in the estimation of energy proxy according to Equation 1.

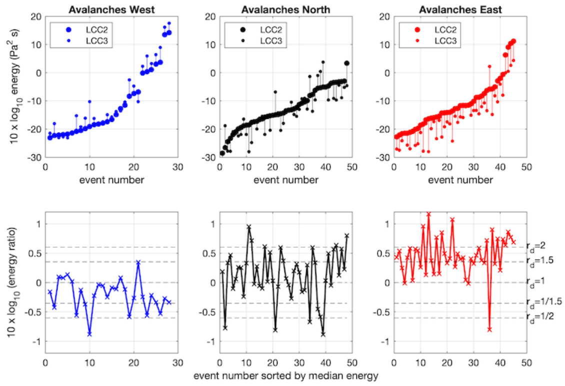

Figure 7 – Avalanches are grouped in to the regions described in Table 1. In the top row of panels energy proxy is shown with logarithmic scales so that both large and small events can be compared. The bottom row of panels show the ratio of energies recorded at LCC relative to LCC3

Although the complete 2022-2023 catalog has not yet been fully analyzed a subset comprising some 37 events reveals some preliminary results (Figure 8). A comparison of D-scale and infrasound energy proxy (measured according to Equation 1) shows the correlation of these two parameters along with significant scatter. The plotted regression lines have large residuals and this suggest one or more of the following points as explanation: 1) distance between avalanche and infrasound recording sites are not considered, 2) infrasound can be variably impacted by changing conditions such as snowpack muffling and/or propagation effects, 3) avalanche sizes in terms of D-scale are hard to quantify and have large 'error bars', or 4) D-scale and infrasound do not relate well in all cases. Perhaps the acoustic radiation depends upon poorly understood parameters such as flow density, flow speed, or source area occupied by the avalanche.

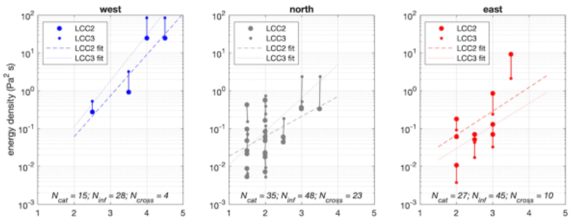

Figure 8 – Comparison between D-scale on the x-axes with infrasound energy proxies on the y-axes grouped in to west, north, and east zones according to Table 1.

6. CONCLUSIONS

More opportunity remains to quantitatively compare D-scale and infrasound energy proxies. A first step would be to take into account distance propagated between avalanche source and infrasound stations. This can only be robustly done after avalanche locations are properly mapped and properly associated with forecaster avalanche sizes. The catalog from LCC in 2022-2023 currently has some ambiguities in terms of associations between infrasound signals and forecaster D-scale estimates owing to a few factors. These include timing uncertainties of forecaster logs (accurate to within a few minutes) and/or multiple avalanches that occur in close succession. In addition, it is important to mention that forecaster D-scale estimates are often subjective approximations and can be hindered by a difficult work environment with subpar visibility. Despite these challenges, it is evident that there is a relationship between infrasound energy and D-scale (Figure 8). Moving forward an empirical relationship between infrasound energetics and avalanche size is a tractable objective and LCC remains an excellent natural laboratory to accomplish this goal. Using infrasound to remotely assess whether an avalanche hits the road is a primary objective

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We remember Liz Clabaugh and eight others who died in a snow avalanche in California on February 17th, 2026. Liz was friend and family to the authors of this paper. This research is dedicated to her.

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