DETECTION AND TRACKING OF SNOW AVALANCHES IN LITTLE COTTONWOOD CANYON, UTAH USING MULTIPLE SMALL-APERTURE INFRASOUND ARRAYS

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ABSTRACT: Two two-element arrays are used to effectively track the progression of snow avalanche in Utah's Little Cottonwood Canyon during triggered and natural cycles in 2018. We describe the steps used to both triangulate these moving sources, and characterize their spatial errors, using integrated beam forming from two arrays. The two infrasound arrays separated by ~10^3 m and possessing ~$10^{1.5}$ m apertures permit efficient triangulation for explosion triggers and moving snow avalanche sources occurring within about 2000 m from the arrays. During the 2018 season, we detect moving sound sources from hundreds of snow avalanches corresponding to class 1 and 2 avalanches. In many cases we are able to track the sound source(s) traveling down well-known slide paths for more than a kilometer and with speeds up to about 10^1 m/s, which we consider as a lower bounds on the actual speed of the advancing flow front. Although three arrays were deployed in 2018 and each comprised four infrasonic microphones, we demonstrate that a subset of four sensors (distributed between two arrays) is especially well suited for quick processing, effective detection, and precise location of the moving avalanche sources. We provide recommendations on the most effective topologies and processing techniques for monitoring avalanche-prone transportation corridors such as Little Cottonwood Canyon.

KEYWORDS: Avalanche detection, infrasound, network of arrays

1. INTRODUCTION

Infrasound study of avalanches is an established monitoring strategy for both long-distance detections using arrays [Bedard et al., 1988], and near-source monitoring [e.g., Adam et al., 1998; Comey & Mendenhall, 2004; Ulivieri et al., 2012]. Havens et al. (2014), for example, used a 3-element infrasound array to track a large avalanche occurring in Idaho along the Route 21 corridor. By constraining the source locations to well-defined chutes mapped with airborne LiDAR, they were able to measure flow speeds of ~40 m/s and signal duration of about 60 s. When avalanche path is not known a network of infrasound arrays has been shown to be effective to locate the absolute positions of moving sources [e.g., Durand et al. (2013)].

Infrasound monitoring in Little Cottonwood Canyon (LCC), Utah has been seasonally operational since 2006 to minimize risk to winter recreationalists and workers [Vyas, 2009]. Infrasound hardware and telemetry were deployed and maintained by InterMountain Labs (IML) to provide monitoring for Highway SR-210, which gives the only access to the popular ski resorts of Snowbird and Alta. During season an average of 7000 vehicles drive to and from these resorts and congestion during periods of elevated traffic (>10000 vehicles) create conditions with high avalanche exposure to the public [Fehr & Peers, 2018]. Sixty-four named slide paths have runouts, which intersect SR-210 and during the 47 year period ending in 2018 there have been 229 natural avalanches and 335 controlled avalanches reaching the road, including 38 while the road was open [Utah Department of Transportation database]. The last significant avalanche to hit the open road was in February 2016.

This report summarizes the efforts conducted in 2018 to improve upon infrasound surveillance of snow avalanches in LCC. Our team deployed monitoring apparatus at the sites occupied since 2006 by the IML installations (Figure 1). This ~1.2 km section of SR-210 is the most exposed to avalanche hazard and contains six named chutes, including White Pine Chutes, White Pine, and Little Pine. Because the IML network is nearing the end of its lifespan we are looking forward to providing enhanced monitoring solutions. Innovations in sensor technology and signal processing have been implemented to improve event localization results (for both ava-

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lanches and triggers), assess location errors, and improve functionality and access to results with a Google Earth interface. Our eventual objectives are to provide telemetry and expand monitoring efforts beyond the Little Pine and White Pine region and provide coverage for the entire canyon. The broader impacts of this work will be to improve avalanche detection capabilities for both Transportation Avalanche Research Pool (TARP) members and other organizations.

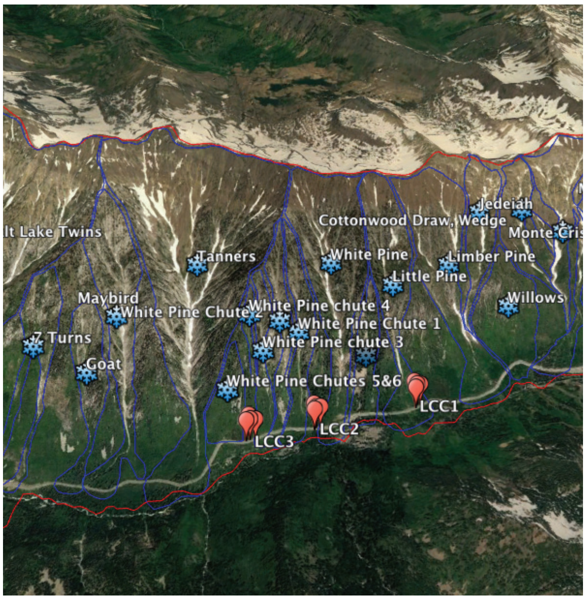

Figure 1 – Oblique north-directed view of LCC and three station array deployment (red push-pins) during winter of 2018. Red polygon represents avalanche search region, which is approximately 6 km east to west, and blue polygons indicate named avalanche slide paths. The BSU2018 instrumentation, consisting of three 4-element arrays, occupied the same sites as the IML installation.

2. DATA COLLECTION

Hardware was installed by our team in December, however the snow season arrived late and the first avalanches and control work began in January. BSU2018 data were recorded using infraBSU pressure transducers possessing specifications similar to the MEMS-based infrasonic microphones described in Marcillo et al. (2012). These sensors have a flat frequency response in the band from ~0.05 Hz to about 50 Hz, which is half the 100 Hz sampling frequency. Data were recorded continuously on 3-channel DataCube 24-bit loggers using built-in 64 times gain. The noise floor, or smallest resolvable infrasound signal in the near-infrasound 1-20 Hz band is about 3 mPa. DataCube loggers tag all data streams with precise timing using GPS allowing accurate time comparisons between sensors recorded with different loggers. Sensor node locations were mapped using a mapping-grade Trimble GeoXH 6000 GPS providing microphone locations accurate to within ~10 cm. Each of the three arrays possessed ~50 m apertures and the four microphone elements were connected to the central logger with cables (Figure 2). Station separation was approximately 1.2 km between LCC1 and LCC3 (Figure 1,2).

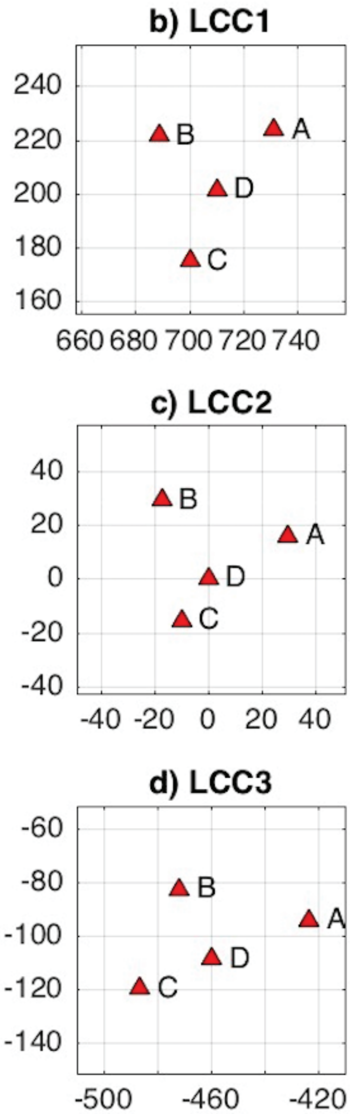

Figure 2 – Array geometry and locations (in meters) relative to LCC2 channel D.

3. DATA ANALYSIS

Infrasound source detections require quantification of lag times between array elements. Cross correlation of infrasound data from two different array elements is effective for identifying time windows when coherent signal passes multiple elements of an array. Continuously collected data is analyzed by subdividing it into overlapping time windows and performing cross correlation after appropriate signal conditioning and filtering. The processed data product is a *corre-*

logram, or matrix whose columns are normalized cross correlation time series for successive windows. This matrix can be displayed graphically (Figure 3) where the dependent variable is the normalized cross correlation coefficient. Events may be visually identified as brightly colored bulls-eyes corresponding to timing of high signal correlation.

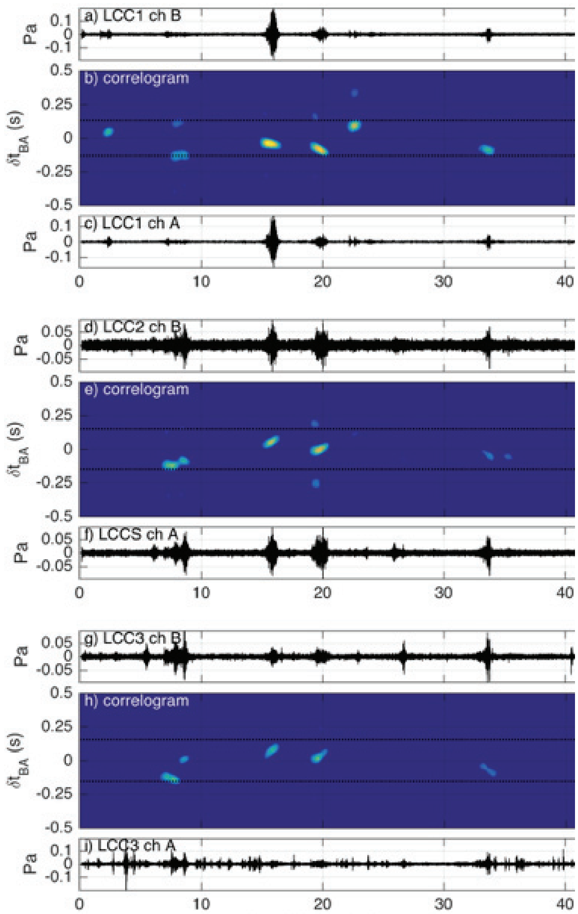

Figure 3 – Correlogram example beginning 19-Feb-2018 at 01:00 local time (08:00 UTC) associated with a natural avalanche cycle during which about six events are evident in 40 minutes. Data presented are from a-c) LCC1, d-f) LCC2, and g-i) LCC3 channels B and A filtered with a 4 pole filter between 3-13 Hz. This correlogram was constructed using 10 s windowed time series with 5 s overlap. Solid black lines indicate the range of lag times expected for LCC search region.

4. MODELED LAG TIMES

For avalanche sources that are local (< few km) to the LCC1-3 network we assume that infrasound propagation approximates a line-of-sight trajectory and that sound speed *(c)* is uniform and isotropic (i.e., there is no wind advecting the sound). In this case time-of-flight between candidate source locations and infrasound microphones may be estimated using a digital elevation model (DEM) and GPS-surveyed locations of microphones. Candidate avalanche source locations are presumed to be at ground level and are thus approximated by the DEM, i.e. $z(x,y)$. In the case of the LCC avalanche study we use the ASTER Global DEM with ~30 m resolution to compute straight-line distances, i.e. for station i located at i_x, i_y, i_z:

$$D_i(x_0, y_0) = \sqrt{(x_0 - i_x)^2 + (y_0 - i_y)^2 + (z_0 - z(x_0, y_0))^2}$$

Flight time for an assumed homogeneous sound speed (c) is then $t_i = D_i/c$. Source-receiver flight times for two sensors are calculated as a differential time, i.e. $\delta t_{ji} = t_j - t_i$ and correspond to the *lag time* for sound arriving at a spatially separated pair of microphones. Lag time maps can be saved as look-up tables and easily compared with lag times of data computed at an individual array (see next section).

In our processing we are able to make effective use of data from only two microphones in each array. This is a subset of the array that permits faster and more simple processing and greater azimuthal precision for the infrasound source. There is an ambiguity, however, as signal arriving at a pair of stations with a certain delay time can be associated with sound coming from two different directions. The correct direction is readily distinguished by: 1) using timing information from a third element in the array, 2) using two different stations in the network, or 3) limiting candidate source locations to distinct regions. In the case of the LCC study area we remove the ambiguity by searching for candidate snow avalanche sources originating north of SR-210 and extending up as far as the ridge line 1.5 to 2.0 km from the road.

5. SOURCE TRIANGULATION

Two (or more) arrays may be used to uniquely triangulate infrasound source locations, whose errors relate to the azimuthal accuracy and precision of each array and to the source position of the arrays within the network. While accuracy is affected by the correct choice of sound speed and surveyed locations of the sensor nodes, precision is largely a function of the source position as it relates to the array geometries (i.e. orientation and separation of sensor pair, which is best when sensor pair is aligned parallel to the wave front). For a candidate source location its associated spatial precision may be quantified as the root-mean-squared norm. For example,

$$\varepsilon(x,y) = \sqrt{\frac{1}{n}\sum_{k=1}^{n}[\delta t_k(x,y) - \delta t_k(x_0,y_0)]^2}$$

where k denotes any number of sensor pairs within a given array and n indicates the number of unique pairs used in analysis. The error ε gives the misfit, in s, between predicted lag times for a source at x_0, y_0 and the lag times that would be measured at x,y. Maps quantifying network location precision capabilities are constructed by illustrating ε contours around candidate source locations. Larger polygons indicate greater uncertainties (Figure 4).

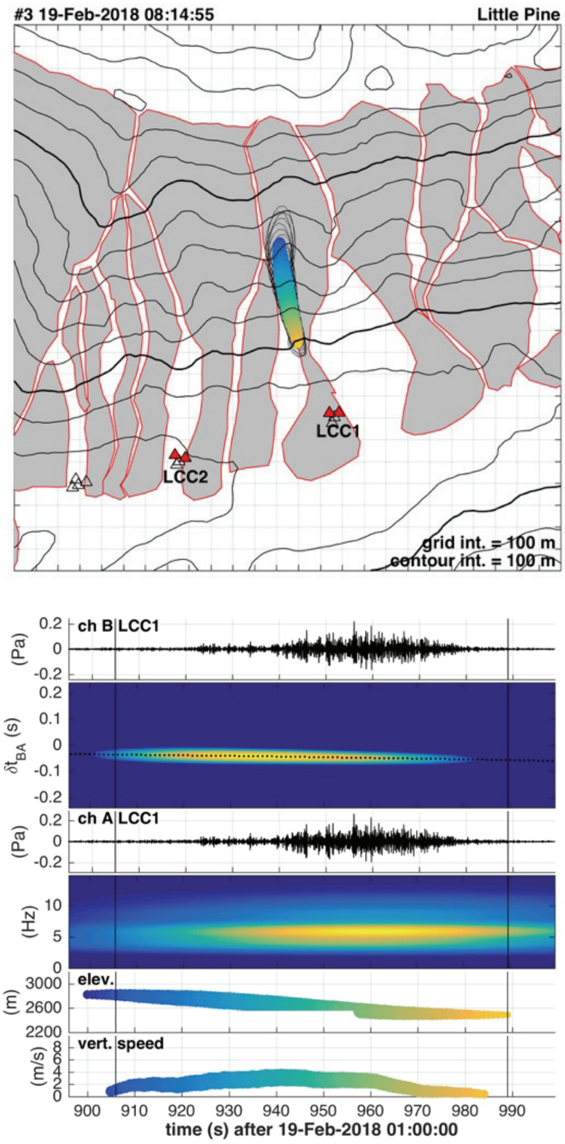

Figure 4 – (top) Map of locations for Little Pine avalanche event #3 located using channels A and B from LCC1 and LCC2. Polygons are drawn with uncertainty $\varepsilon = 0.01$ s. (bottom) Infrasound time series (filtered 3-13 Hz), correlogram, spectrogram displaying spectral information, and source centroid elevation and vertical speed progression for the duration of the detection.

Visualization of infrasound-derived moving avalanche sources is easily availed in GIS software such as Google Earth (Figure 5). Location output can be time-tagged and conveniently viewed in perspective. Hyperlinks can direct interested parties to the information contained in Figure 4.

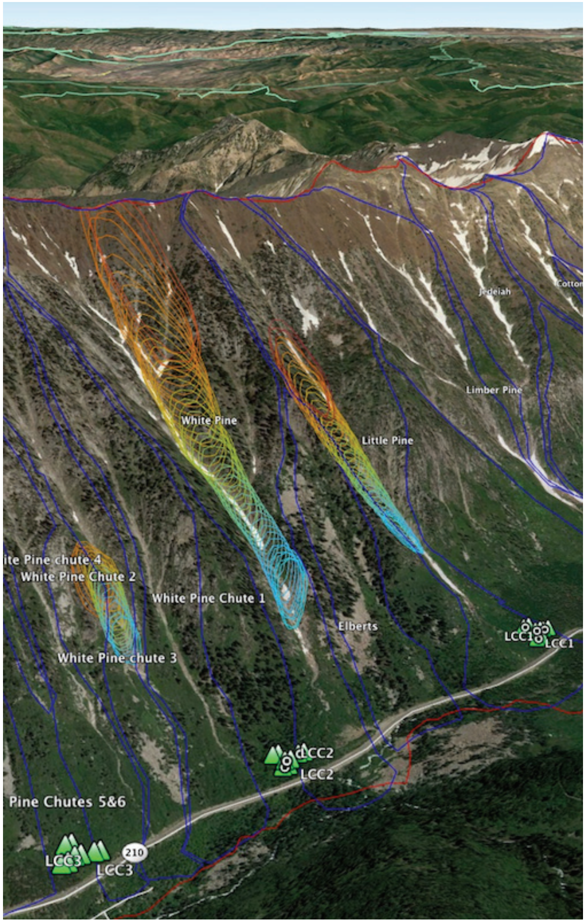

Figure 5 – Google Earth visualization of three avalanches occurring during the natural cycle shown in Figure 3.

6. CONTROL WORK TRIGGERS

Artillery infrasound may be processed similarly and mapped as point locations (Figure 6). Precise location of explosion triggers is important for forecasters wishing to verify accuracy of a shot. For explosion triggers the sources are non-moving (with fixed lag times), produce high amplitude impulsive infrasound (as opposed to tremor-like avalanche signals), and are easy to identify in the correlograms. Source location is somewhat dependent upon selection of atmospheric sound speeds, which depend upon ambient temperature. For the mid-canyon slide paths uncertainty in temperature may give rise to location errors on the order of 10^1 m.

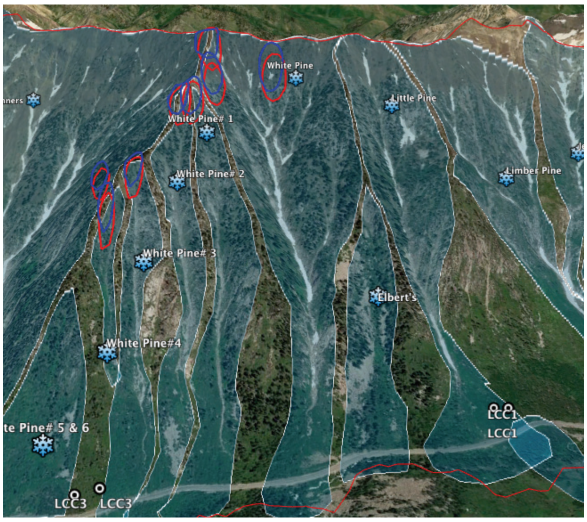

Figure 6 – Eight artillery triggers and their infrasound-derived locations using two elements from the arrays LCC1 and LCC3. Polygons denote $\varepsilon = 0.01$ s uncertainty. Red and blue locations correspond to assumed 325 m/s (-18°C; 0°F) and 332 m/s (0°C; 32°F) sound speeds respectively.

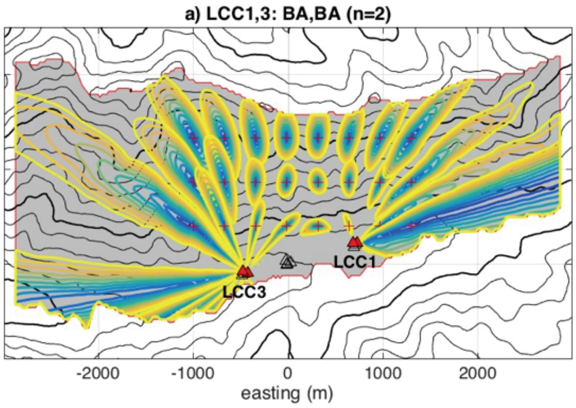

Figure 7 – Location sensitivity for sources occurring in LCC and located using only stations LCC1 and LCC3. Outermost ellipses (yellow lines) correspond to $\varepsilon = 0.01$ s uncertainty. This analysis shows that sources occurring within the network and internal to LCC1 and LCC3 will be located with greatest precision.

7. CONCLUDING REMARKS

Dual infrasound arrays are effective at precise location of both moving sources (avalanches) and fixed location sources (explosions) provided that the sources occur within the interior of the station network. The BSU2018 deployment in LCC succeeded well in locating events occurring in Little Pine and White Pine slide areas, but events occurring outside this zone are relatively imprecisely triangulated. Location sensitivity may be estimated by using synthetic data and calculating the spatial uncertainty of sources associated with a fixed timing error (Figure 7). Performing such analyses can be used to better determine optimal station topologies. We plan to use such modeling to inform an enhanced deployment for the winter of 2018-2019 when we return with an expanded network of arrays.

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