Comparison of Doppler radar to thermal infrared rockfall detection

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Abstract

As part of the thermal imaging for rockfall detection project, trials were run to compare thermal imaging with Doppler radar technology. A trial was conducted at the Teck Resources Highland Valley Copper (HVC) mine. The IDS RockSpot Doppler radar system was collocated with a thermal imaging system consisting of four thermal cameras on board a Mobile Monitoring Platform (MMP) developed by the Geotechnical Center of Excellence (GCE). The systems monitored natural and mining-induced rockfall events for three months. In addition, a controlled rockfall drop test was conducted, in which rock blocks of known dimensions were rolled down a snow-covered overspill slope. Fields of view varied for the RockSpot and the thermal cameras; as a result, the systems did not capture all the same events. Engineers reviewed the thermal video for rockfall events that occurred within the field of view of both systems. This paper presents a comparison of the systems effectiveness in detecting rockfall related to large blast events and the controlled drop tests. Results indicate that both systems are useful applications for adapting existing technology to mining applications. Based on the findings presented here, the authors recommend integrating the two different monitoring tools into a single detection system that can provide verification and authentication of rockfall events with additional reliability through the use of two different segments of the Electro Magnetic spectrum.

1 Introduction

The Thermal Imaging project for Rockfall Detection Mobile Monitoring Platform (MMP) was deployed at Teck Resources Highland Valley Copper mine (HVC) in British Columbia, Canada, between October 26, 2021, and January 24, 2022. An IDS RockSpot Doppler radar system was collocated with the MMP during the same timeframe. Both units were placed on a buttress on the east side of the pit on the 3,900 level. The approximate distance between the systems and the slope was between 1,050 meters to the toe and 2,000 meters to the crest (3,500 ft and 6,500 ft). Both systems were initially pointed southwest towards an active fault zone and then later pointed at an overspill slope for controlled rockfall drop testing. During the deployment, both systems captured several natural rockfalls, multiple blasts, and a planned synthetic rockfall test where rocks of known size were dropped over the crest by a loader to demonstrate the capabilities of both systems. This paper presents a comparison of the systems effectiveness in detecting rockfall related to blast events and the controlled drop tests.

1.1 Doppler radar and thermal infrared imaging

Doppler radar is an active monitoring system that uses the Doppler shift information from the radar signal to detect a moving object and then determine the movement of that object within the field of view (Richards et al., 2010). IDS has developed software, GeoCloud, to complement the RockSpot Doppler system using advanced signal processing techniques to generate georeferenced tracks of rockfall events and provide relevant details about the event, including runout distance, surface area, release time and duration, as well as intensity and front velocity heat maps (Michelini et al., 2020). The alerting capability of the system is still in development.

Thermal imaging systems detect rockfall from temperature changes that occur as a rock detaches, rolls, impacts, and scours a slope (Wellman et al., 2022). Thermal imaging is a passive system in which no electromagnetic signal is transmitted. Thermal cameras are commercially available; however, automated tracking systems for identifying and alarming in response to rockfall events are still in development.

Both systems can be used 24 hours a day, including during moderate rainfall and snowfall, but have some limitations during heavy precipitation events and fog.

2 Systems specifications

Four thermal cameras with various fields of view and resolutions were acquired and mounted on the MMP for the GCE's ongoing thermal imaging research. These cameras consist of one scientific camera (CAM1), two security cameras (CAM2 and CAM3), and combined thermal and optical pan/tilt/zoom (PTZ) camera (CAM4). The IDS RockSpot Doppler Radar includes a single visual camera and doppler radar coverage, both with a wide-angle view.

This section will detail each system's fields of view, resolution, and detection limits.

2.1 Fields of view

The RockSpot Doppler radar has a wider field of view than any of the thermal cameras on board the MMP. Table 1 lists the focal length, horizontal field of view (HFOV), and vertical field of view (VFOV) for each system. Figure 1 illustrates a comparison between each field of view. The thermal imaging system did not capture rockfalls outside the cameras field of view.

2.1.1 Thermal camera system

Fields of view vary for each of the cameras and are a function of the focal length of the imaging plane on the camera. Table 1 shows that three cameras have set focal lengths and fields of view, while the AXIS Q8752E (CAM4) is variable due to its zoom capabilities. This functionality makes CAM4 more of a visual or situational awareness tool. The FLIR A400 (CAM1), FLIR FC-632-ID (CAM2), and AXIS Q1941E (CAM3) are all fixed cameras (without PTZ capabilities) that are manually pointed towards the area of interest. CAM2 has the widest field of view and captured most of the area of interest for this study.

Table 1. Thermal camera and RockSpot specifications

Specifications	CAM1 FLIR A400	CAM2 FLIR FC-632-ID	CAM3 AXIS Q1941E	CAM4T AXIS Q8752E	CAM4V AXIS Q8752E	IDS RockSpot
Resolution (pixels)	320x240	640x480	320x240	640x480	1080p	-
Focal Length (mm)	29	19	35	varies	varies	-
HFOV	14°	32°	10.5°	6°-18°	2.4°-35°	80°
VFOV	10°	26°	8°	4.5°-13°	1.3°-34°	40°

2.1.2 Doppler radar

The RockSpot Doppler has a HFOV of 80° and a VFOV of 40°, as shown in Figure 1. This large view area allows adequate monitoring across an open pit to detect rockfalls in multiple areas. The RockSpot system is designed to operate in a large field; however, detection performance is best in the center of the view and worsens approaching the outer limits (RockSpot User Guide 2020). The large field of view for the RockSpot allowed the system to capture and detect rockfall events that occurred during this trial outside of view of the thermal cameras on board the MMP.

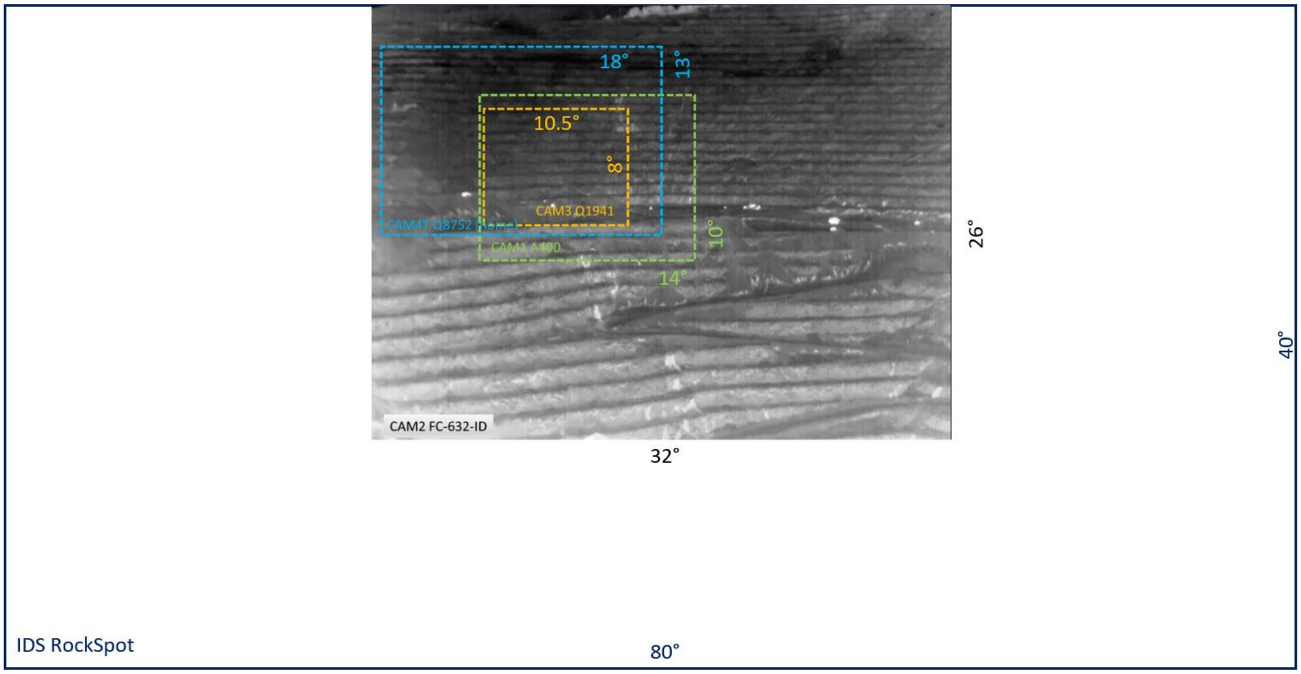

Figure 1. Fields of view of the IDS RockSpot Doppler radar compared to the four thermal cameras on the MMP.

2.2 Scanning Time

The scan time for both systems is comparable. The thermal imaging cameras capture footage in the set fields of view at 15-30 frames per second. The IDS RockSpot scans at 2 Hz giving a scan time of 0.5 seconds for the set field of view. The relatively fast scan times of both systems are important for detecting real-time movements and rockfalls.

2.3 Resolution

Both the thermal camera system and the RockSpot Doppler radar system were able to detect events within and even less than, in some cases, the resolution of the equipment tested. Both systems also detected other movement not related to rock fall, such as birds, mining equipment, and flowing water in drainages.

2.3.1 Thermal camera system

Table 1 details the resolution of the four thermal cameras acquired for this project: CAM1 and CAM3 are considered medium resolution (320 x 240), CAM2 high resolution (640 x 480), and CAM4 is a high-resolution pan/tilt/zoom (PTZ) combination camera with thermal imaging and a 1080p visual camera. Table 2 lists the thermal camera resolution at 1,500 meters (5,000 ft) to the rockfall test location.

During this trial, the thermal cameras captured and detected several natural rockfall events, most of which were preceded by adverse weather events. The thermal cameras also recorded rockfall initiated by mining equipment and by a controlled synthetic rock drop test. The thermal cameras also detect other moving objects in the scene, including the mining equipment and birds.

Table 2. Thermal camera resolution at Mine-6 (Range 1,500 m)

Specifications	CAM1 FLIR A400	CAM2 FLIR FC-632-ID	CAM3 AXIS Q1941E	CAM4T AXIS Q8752E
Resolution	QVGA	VGA	QVGA	VGA
Calculated Pixel Size (cm)	88	134	73	67
Calculated Pixel Size (ft)	2.9	4.4	2.4	2.2

2.3.2 Doppler radar

The RockSpot Doppler radar can effectively monitor a large section of open pit walls at high resolution with a large field of view. The RockSpot's resolution is four meters (13.1 ft) by one degree, meaning that at 1,500 meters, the system can resolve two events that are four meters apart in range (i.e., along the line-of-sight of the radar system) and 25.5 m (83.6 ft) in azimuth. However, detection probability increases with boulder size, and falling rocks with smaller dimensions may not be detected by the system (RockSpot User Guide 2020). During daylight hours, rockfall events detected by the RockSpot were recorded in real time by the visual camera, as shown in Figure 7.

2.4 Detection limits

Both thermal cameras and Doppler radar can detect and capture rockfalls at the distances tested as part of this study. While the thermal cameras use temperature change to detect rockfalls, the RockSpot uses Doppler radar technology to detect and track rockfall events. The RockSpot is georeferenced using global navigation satellite system (GNSS) and regularly updated digital terrain models (DTM) to accurately track the location of rockfalls. The thermal cameras are not currently georeferenced.

2.4.1 Thermal camera system

The thermal cameras used for this project can capture and detect rockfall across large open pit mines. The largest range to date is approximately 2,500 meters (8,000 feet) to the slope. Synthetic rockfall tests with various size rocks have proven that rockfall less than pixel resolution for each camera can be detected by the impact cratering and dusting that occurs with the rockfall event. Figure 3 demonstrates this with small black spots in a line down the slope's lower right side, indicating fresh disturbance from a rockfall during a controlled test.

2.4.2 Doppler radar

The IDS RockSpot Doppler radar system can detect and track rockfall approximately 2,000 meters (6,500 feet) and within the field of view. Trackable rock sizes vary based on the distance from the radar. Events that have large radar cross sections, including events from small rocks that generate dust clouds as they fall down the slope, are detectable by the RockSpot as well. The RockSpot has a minimum Doppler velocity of one m/s (2.2 mph), so events moving above that velocity will be detectable (RockSpot User Guide 2020).

2.5 Comparison for the period of October 28 to November 4, 2021

Personnel from the GCE and IDS reviewed events to identify and classify rockfalls on both systems for the period of October 28 to November 4, 2021. The RockSpot identified thirty events in the period. The bulk of these events were located to the left of the Lornex Fault Zone (LFZ), outside view of the thermal cameras. The direction of the thermal camera field of view was selected in order to capture rockfalls associated with the LFZ and the active mining areas to the center and right of the field of view. During the same period, five rockfalls that occurred within the field of view of the thermal cameras were identified by both systems.

Due to time and personnel constraints, a detailed analysis of the remainder of the trial (outside the October 28 to November 4, 2021 period) has not been completed. Thermal video detection and tracking require scanning through thousands of hours of video to identify events. The RockSpot system, though it has an automated detection and tracking system, still requires user verification of the event.

3 Control test

A controlled synthetic rockfall test was conducted at the mine on January 11, 2022, where four separate controlled drops were conducted with various known-sized boulders. This test was completed by mechanically dropping rocks off the edge of a snow-covered overspill slope with a loader. Boulders ranged from as large as three meters (ten feet) to as small as one meter (three feet). Table 3 details the four controlled drops completed, and Figure 2 shows a mining loader carrying one of the boulders that was dropped as part of the test.

Table 3. Synthetic rockfall test on January 11, 2022.

Drop #	# of Boulders	Boulder Size (m)	Boulder Size (ft)	Time (PDT)
1	1	3	10	12:52:41
2	1	1.5	5	12:56:59
3	Many	Small	Small	13:00:51
4	3	1.8, 1.5, 1	6, 5, 3	13:07:11

Figure 2. Mine loader carrying a boulder to be dropped for synthetic rockfall test.

Figures 3 and 4 show the same rock drop test from CAM2 and RockSpot. Figure 3 shows how thermal imaging captures rockfall with small impact craters denoted by small black dots down the slope.

Figure 4 demonstrates how the RockSpot Doppler radar can detect, track and trace a rockfall event on a digital terrain model (DTM) on the left image, shown with a red track, and associated visual imagery with the camera on right image. This figure demonstrates the need for frequently updated and accurate DTMs in the RockSpot system to more accurately track events as it appears in this image that the rockfall initiates mid-bench when it is actually from the crest.

The synthetic controlled rockfall test proved that the thermal camera system and the RockSpot radar system could detect and record rockfalls of various sizes (Table 3). The thermal cameras could detect the rockfalls, even when the rocks broke into smaller pieces, based on the impacts to the slope. The track generation algorithm utilized by the RockSpot system provides a line representing the average track of an entire rockfall event (rather than separate tracks for individual rocks).

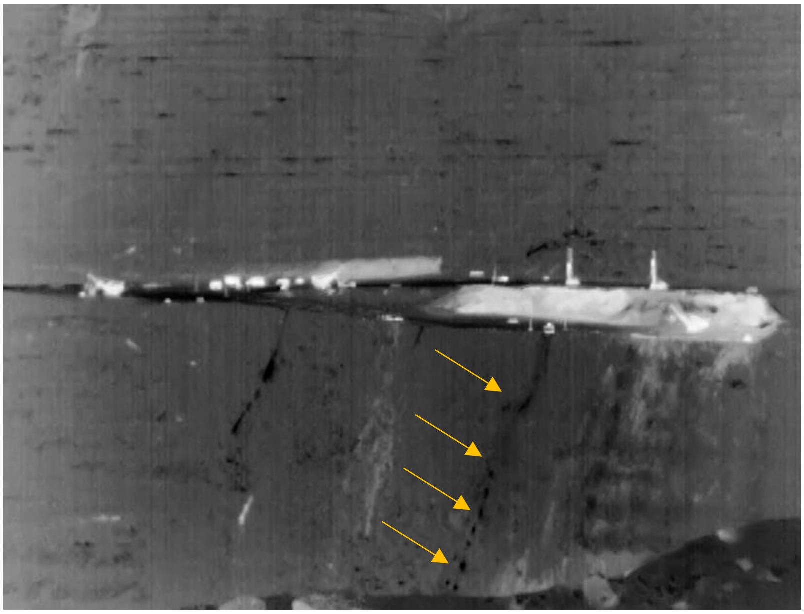

Figure 3. FLIR FC-632-ID (CAM2) thermal camera during controlled synthetic rockfall test.

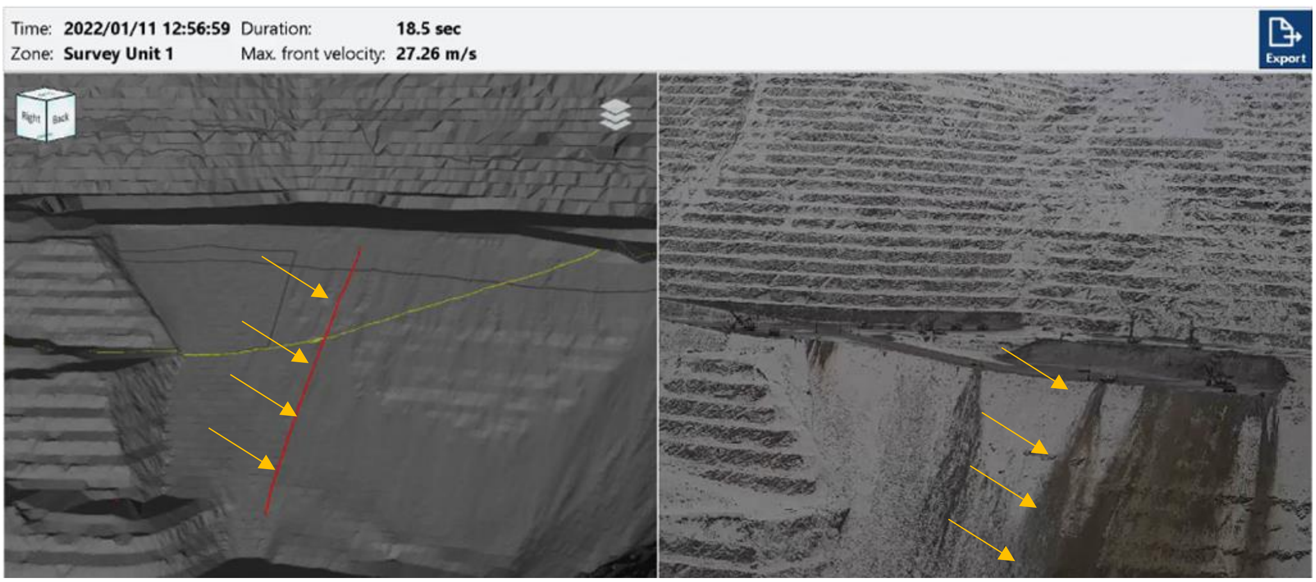

Figure 4. IDS RockSpot Doppler imagery during controlled synthetic rockfall test.

4 Blast event

A blast event initiated on December 7, 2021 was captured by both systems. This blast was located on the pit edge side of the active mining level and resulted in material travelling down the side of the overspill slope. The blast was in the field of view of two of the cameras, and CAM2 captured the entire event in full horizontal view. The lower levels were not captured (Figure 5) due to the camera's position. The thermal cameras that captured the event recorded the heat generated by the blast with respect to the surrounding colder rock surfaces, which is shown in Figure 5 as a white-hot plume. The RockSpot Doppler radar system also captured the blast and could track rockfall down the slope below, as shown in Figure 6. A rockfall intensity heat map generated by the GeoCloud software captures the event's entirety and is shown in Figure 7.

Figure 5. CAM2 thermal imagery capture of a blast event.

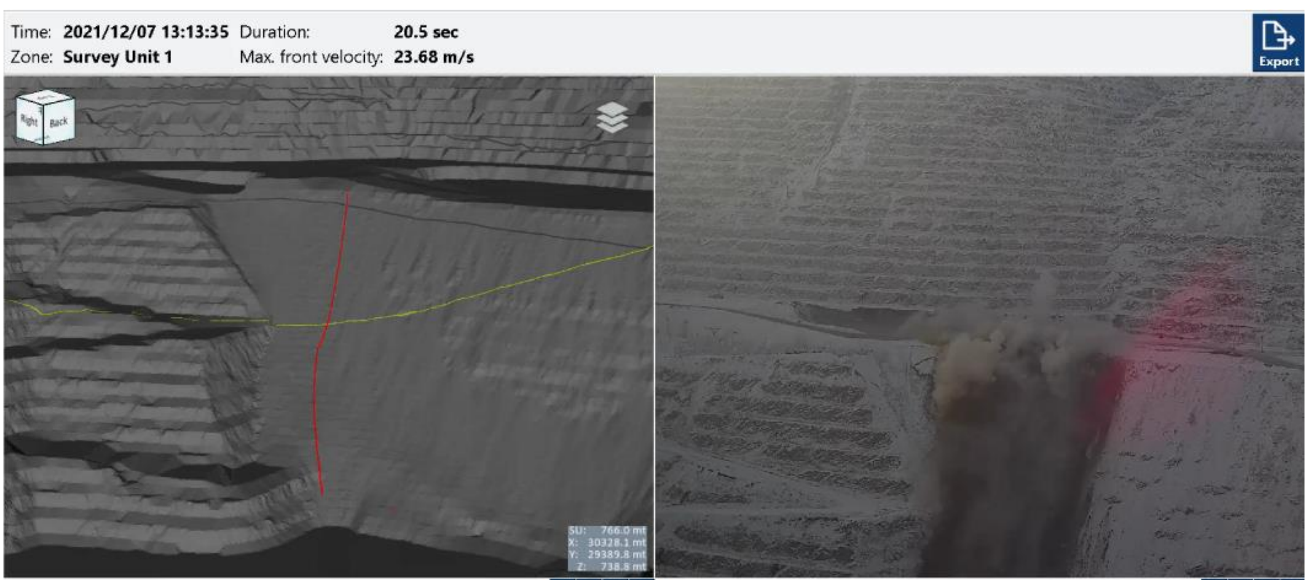

Figure 6. IDS RockSpot Doppler imagery showing a blast event.

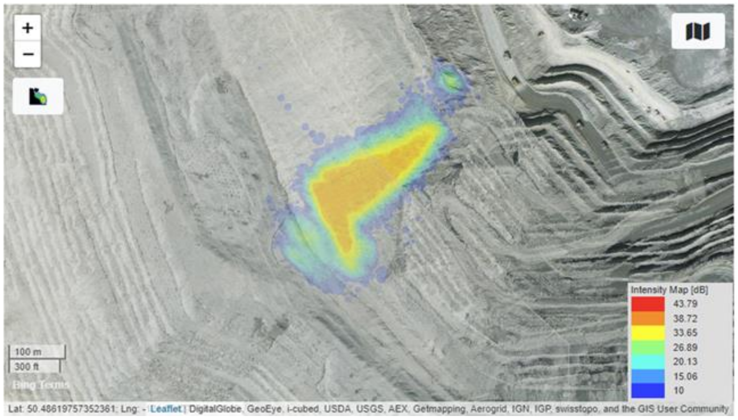

Figure 7. IDS GeoCloud rockfall intensity heat map during a blast event.

5 Natural rockfall

Several natural rockfall events occurred during the trial, the most notable of which occurred on October 29, 2021. Three separate single-bench scale rockfall events were recorded. Heavy precipitation occurred throughout the day. Figure 8 shows each thermal camera view during one of the natural rockfall events located within the LFZ. The ambient surface temperature of the surrounding rock is cooler (darker) than the falling rocks (lighter). Figure 9 shows the same rockfall event as captured by the RockSpot. Note that it appears to be a single bench even in the radar detection, highlighted by the red trace. This is verified by the thermal images shown in Figure 8. Other bright spots in the thermal images are indicative of water seeps as the ground water is warmer than the surficial rock temperature at this particular time of year. Mining equipment is also warmer than in-situ rock and therefore brighter.

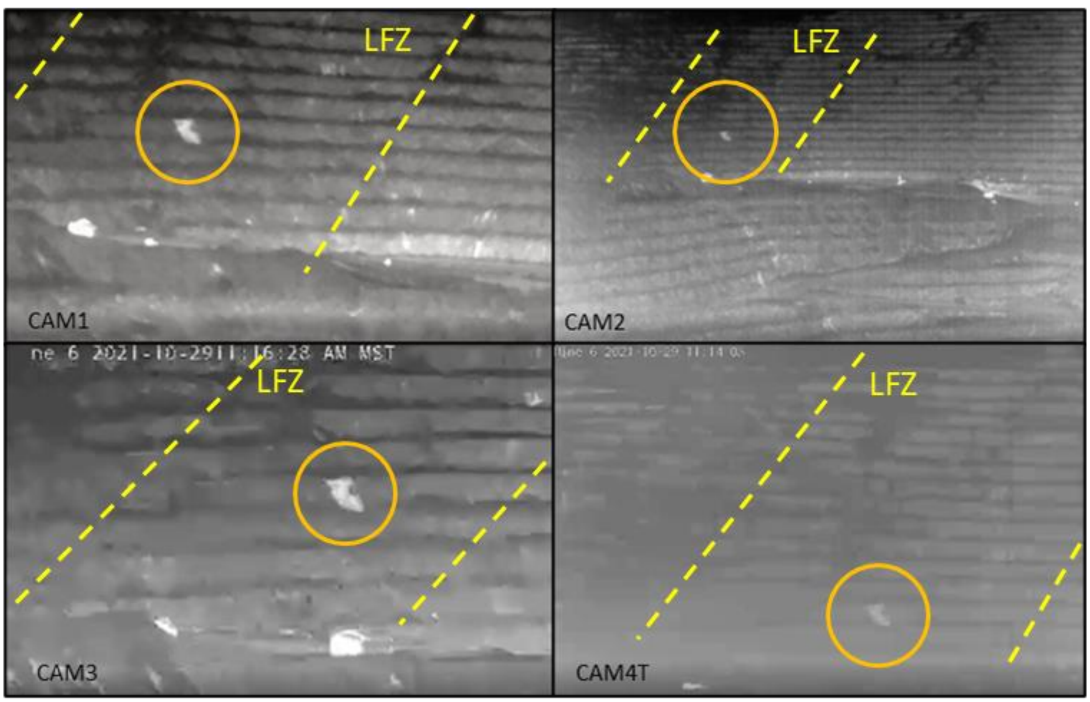

Figure 8. View of a single natural rockfall event within the LFZ from each of the four thermal cameras. Approximate location of LFZ shown in yellow dashed lines.

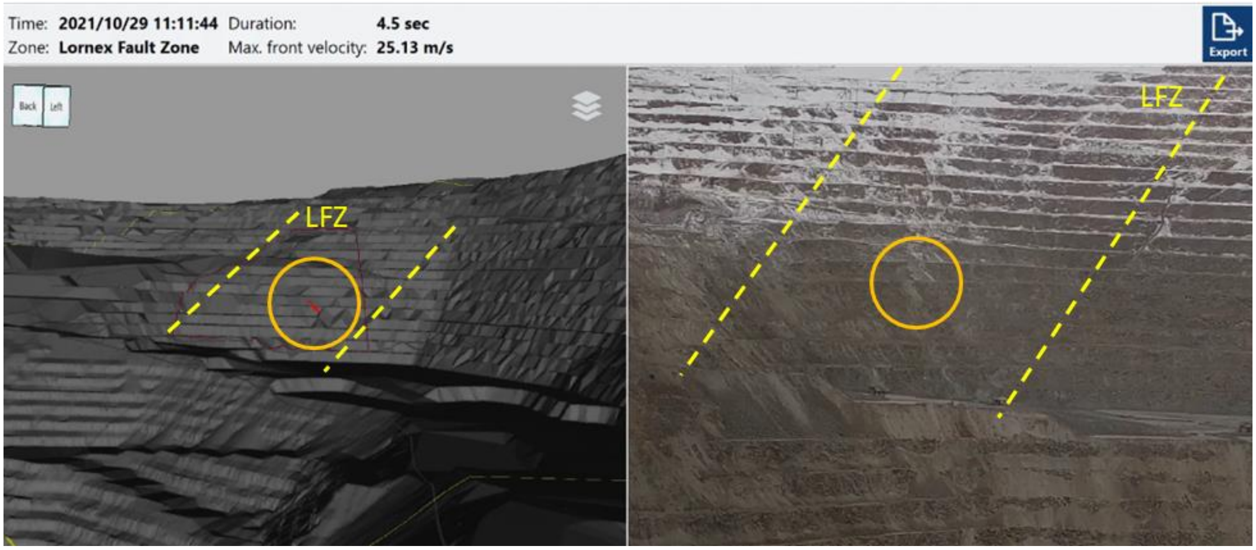

Figure 9. RockSpot radar detection of the same single natural rockfall event within the LFZ captured by the thermal cameras in figure 8. Approximate location of LFZ shown in yellow dashed lines.

6 Limitations

While the thermal imaging cameras and RockSpot Doppler radar have been proven to detect rockfall events, each system also has limitations that affect the quality of data output. Notable differences between the limitations of each system documented as part of this study include:

1. The Doppler radar system can typically capture more rockfalls during atmospheric events due to an atmospheric algorithm that filters out some of the atmospheric noise. The thermal camera systems do not currently have such corrections.
2. While the thermal cameras can detect multiple rockfall events across a scene at one time, the RockSpot's detection capabilities are limited by line of sight, the distance between events, and the velocity of the rockfall.
3. The thermal system does not currently have tracking algorithms in place. This is a major component of the GCE's planned next phases of thermal imaging research.

This section discusses some of the limitations of each system as observed during this test.

6.1 Thermal camera system

Limitations of the thermal camera systems include 1) temperature range scale expansion due to sky view, 2) low visibility during heavy rainfall, snowfall, and blowing dust, and 3) low thermal contrast with extreme climate temperatures.

The sky is always a much cooler temperature than the temperature of the ground. Interpretation of image results from previous test sites indicate that the inclusion of sky in the view of the cameras expands the temperature range scale, which results in a reduction in image contrast. This reduction in contrast reduces the cameras' ability to detect minor changes in temperature used to detect rockfall (Wellman et al., 2022). Therefore, it is important to set the thermal cameras with as little sky as possible in the field of view.

Low visibility that caused degradation of image quality due to atmospheric events was observed during this test period. These atmospheric events included periods of rainfall, heavy snowfall, low cloud cover or fog (low optical visibility), and periods of blowing dust. Figure 10 shows what the thermal cameras capture during a heavy snowstorm.

During extremely cold temperatures, the lowest of which was recorded at this site at -32°C (-27°F), there were several instances where the thermal images had low thermal contrast but good visibility. Low thermal contrast also occurs during overcast and light rainfall conditions.

Figure 10. CAM3 view during heavy snowfall.

6.2 Doppler radar

Limitations of the IDS RockSpot Doppler radar system and associated software include 1) unwanted detections and false detections (e.g., movement of equipment), 2) low visibility of the visual camera at night and due to occasional environmental conditions (e.g., dust), and 3) the necessity for regular digital terrain model (DTM) updates.

Unwanted detections by the radar tracking algorithm results in the detection of events not related to falling rocks, such as detecting a haul truck driving on a ramp or a loader pushing material over the crest (Davidson, 2022). This type of equipment is constantly moving at a mine site and is highly reflective of the radar. Figure 11 shows unwanted detection of a haul truck driving on a ramp by the RockSpot system. Flowing water within the monitoring area can also cause unwanted detections.

The visual camera attached to the radar is not effective during nighttime hours and times of low visibility due to rain, snow, fog, and blowing dust. The visual camera is not required for the Doppler radar to function, but is helpful for visualizing what the radar captures in real time.

Regular updates to the DTM are necessary to manage the geocoding of data in active mining areas where the topography is constantly changing. This helps with the management of user set exclusion zones, which masks unwanted detections (e.g., mining equipment), and is critical for the operation of the RockSpot, especially in areas where equipment is operating.

Additionally, the event detection performance of RockSpot is highly dependent on the rock size, distance to the event, fall angle, velocity of the rockfall, maximum reflected power, and atmospheric conditions in the area. Simultaneous events can be detected and tracked if their instantaneous distances from the sensor differ by at least four meters (13 feet) in the range direction and at least one degree in azimuth (RockSpot User Guide 2020).

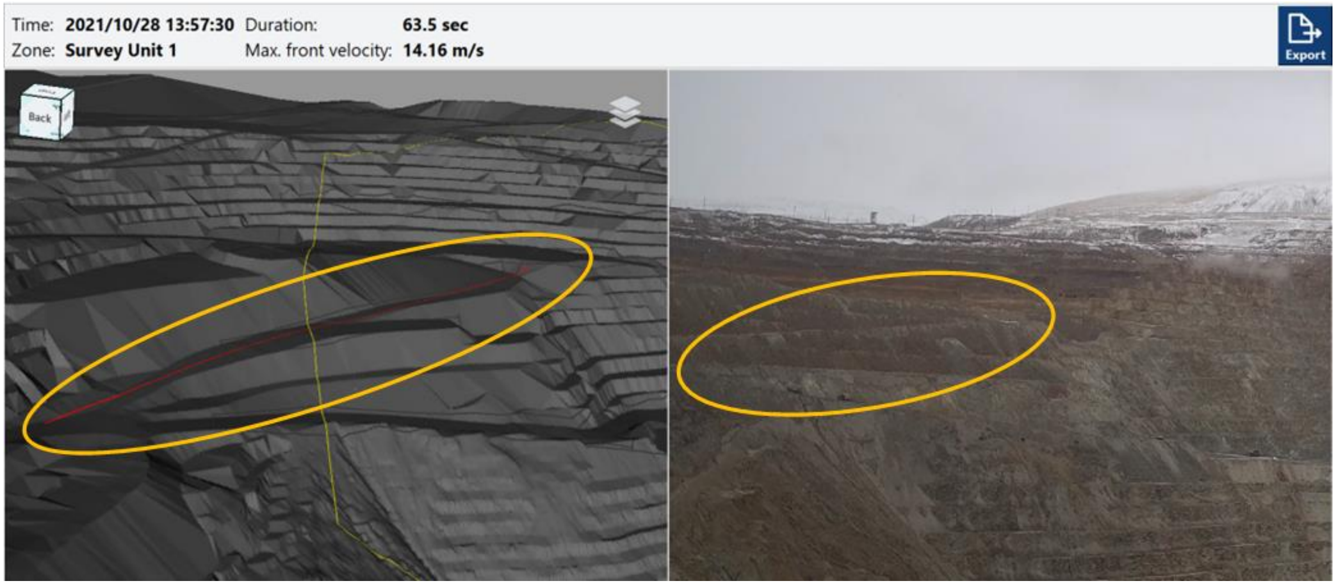

Figure 11. RockSpot Doppler radar "unwanted" detection of a haul truck driving on a haulage ramp.

7 Conclusions and recommendations

The trial documented here demonstrated that thermal imaging cameras and Doppler radar are both useful adaptations of existing technology for rockfall monitoring in open pit mining environments. An example of this occurred on October 29, 2021, when an on-call member of mine geotechnical staff reported, "there were reports of raveling in the field, … and the wall was making a lot of noise". Following the event, engineers reviewed the two systems at the time reported and found that all four thermal cameras and the RockSpot doppler radar successfully captured the rockfall event observed by mine personnel.

Further research is planned for the coming months based on observations made during MMP deployments between 2020 and 2022. Observations and potential future paths include:

1. While deployed at another mine, the thermal imaging system recorded an exponential increase in rockfall events in the days leading up to a large slope failure (Schafer et al., 2022).
2. In the same deployment, the thermal imaging recorded a significant temperature rise (roughly 55 degrees F) along the backplane of a failure plane due to frictional heating in response to a slope failure.
3. The use of thermal imaging in water seep mapping. Every site that the MMP has been deployed to has had water seeps in the walls that the thermal cameras have been able to detect, many of which are difficult to identify in visual camera images or from field observation.
4. Detailed review of the entire period during which both Doppler radar and thermal imaging systems were deployed at the HVC mine to better quantify and compare the systems ability to detect rockfall.

Visual cameras, such as what is already integrated on the RockSpot radar as well as the AXIS Q8752E (CAM4V) on the MMP, are also useful tools to verify events during daylight and clear conditions. However, thermal imaging can detect and capture clearly throughout all 24 hours in a day. Likewise, Doppler radar can detect events at all hours of the day and during some atmospheric events with atmospheric correction algorithms applied.

While both systems are useful and powerful tools individually, it is recommended to integrate the two different systems into a single detection system including Doppler radar, a thermal infrared camera, geospatial positioning, and atmospheric corrections that would most benefit users. Doing this can provide verification and authentication of rockfall events while having additional reliability by using two different segments of the Electro Magnetic spectrum.

Fine-tuning automated detection and tracking algorithms using machine learning or other methods will make both systems more useful for identifying and detecting rockfall. In addition, having a wide field of view for a Doppler radar and thermal camera integrated system would be beneficial as it would potentially allow coverage of an entire pit slope.

8 Acknowledgments

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