Avalanche Detections with Sentinel-1: Controls on Detection Rates

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Introduction

Snow avalanche records have historically come from field observations and consequently been spatially and temporally limited. Remotely sensed avalanche observations show promise in providing more complete databases of avalanche observations. Sentinel-1 is a synthetic aperture radar (SAR) satellite that provides 10-meter resolution and has proven ability in identifying avalanche debris. As a SAR satellite Sentinel-1 can penetrate clouds and is unaffected by darkness. This allows for avalanche detections during storms and polar darkness. Previous research has focused on exploring automated detection methods, and mapping major avalanche cycles. An unexplored question is the primary controls on when an avalanche is detectable in Sentinel-1 imagery. Previous studies have shown a clear size constraint where the spatial resolution of Sentinel-1 is insufficient to resolve the avalanche debris. This study explores not only this size controls on detections, but also avalanche type, local incidence angle, meteorological factors, and topographic effects.

Methods

- Records of field observed avalanches from the Utah Department of Transporation and Bridger-Teton Avalanche Center provided locations, dates, and information on avalanches.
- Reported avalanches had a mean destructive size of 2.39 (standard deviation of 0.76) and were 93.5% dry, 93.3% slabs, and 46% came from the Bridger-Teton dataset.
- Sentinel-1 image pairs with the same orbital geometry were downloaded from prior to the avalanche cycle (reference image) and following the cycle (activity image).
- Changes in Sentinel-1 images were used to manually detect avalanche debris based on significant (2+dB) increase in backscatter in the track or runout of avalanche paths(Figure 1).
- Potential controlling factors (type of avalanche, trigger, d-size, meteorological history (PRISM) and topographic effects) were extracted for each avalanche.

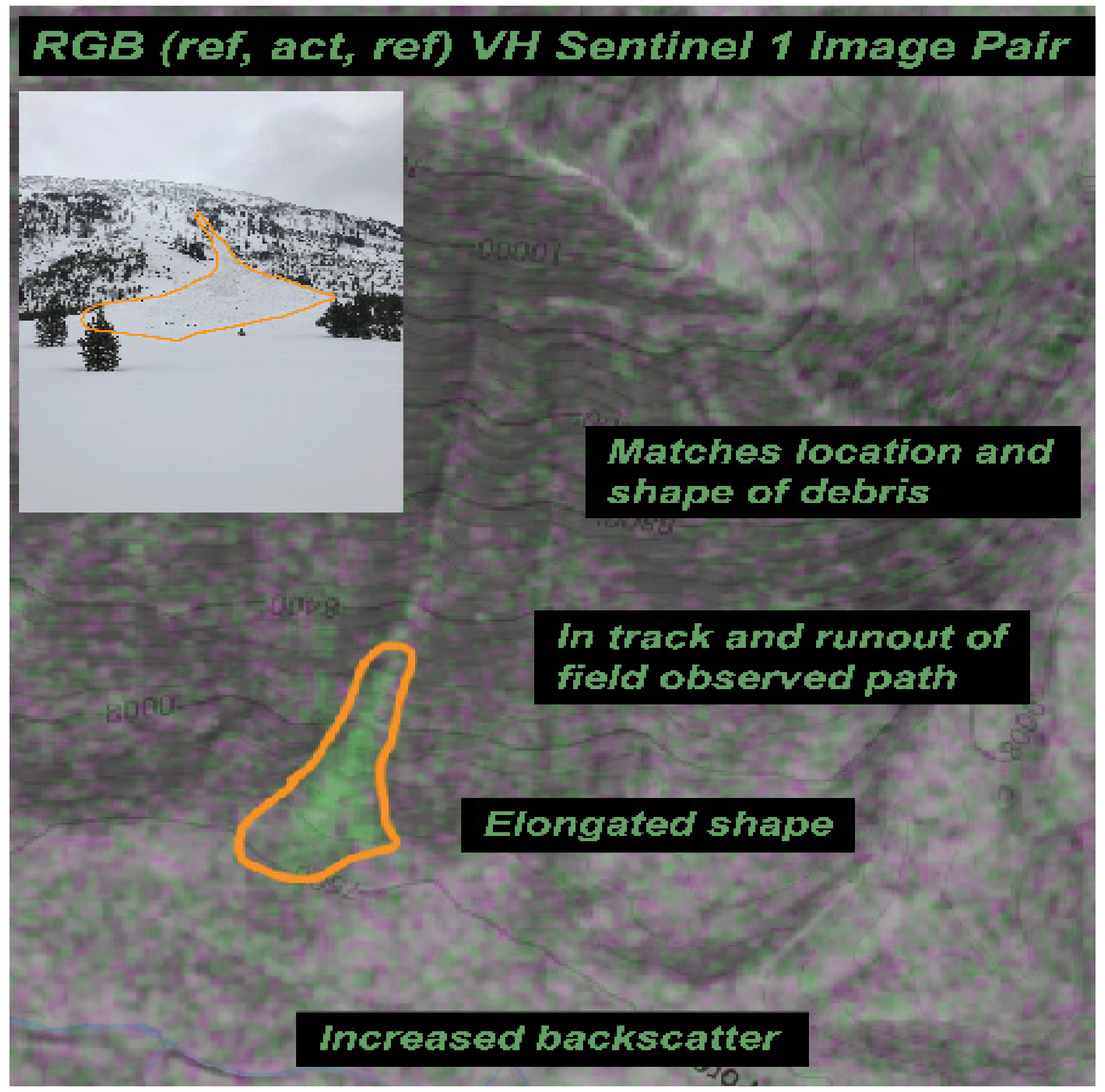

Figure 1: RGB image with reference S1 VH image in the red and blue channels and VH activity S1 image in the green channel. Green represents increases in backscatter and purple represents decreases. Inset field image courtesy of: Bridger-Teton Avalanche Center.

Results

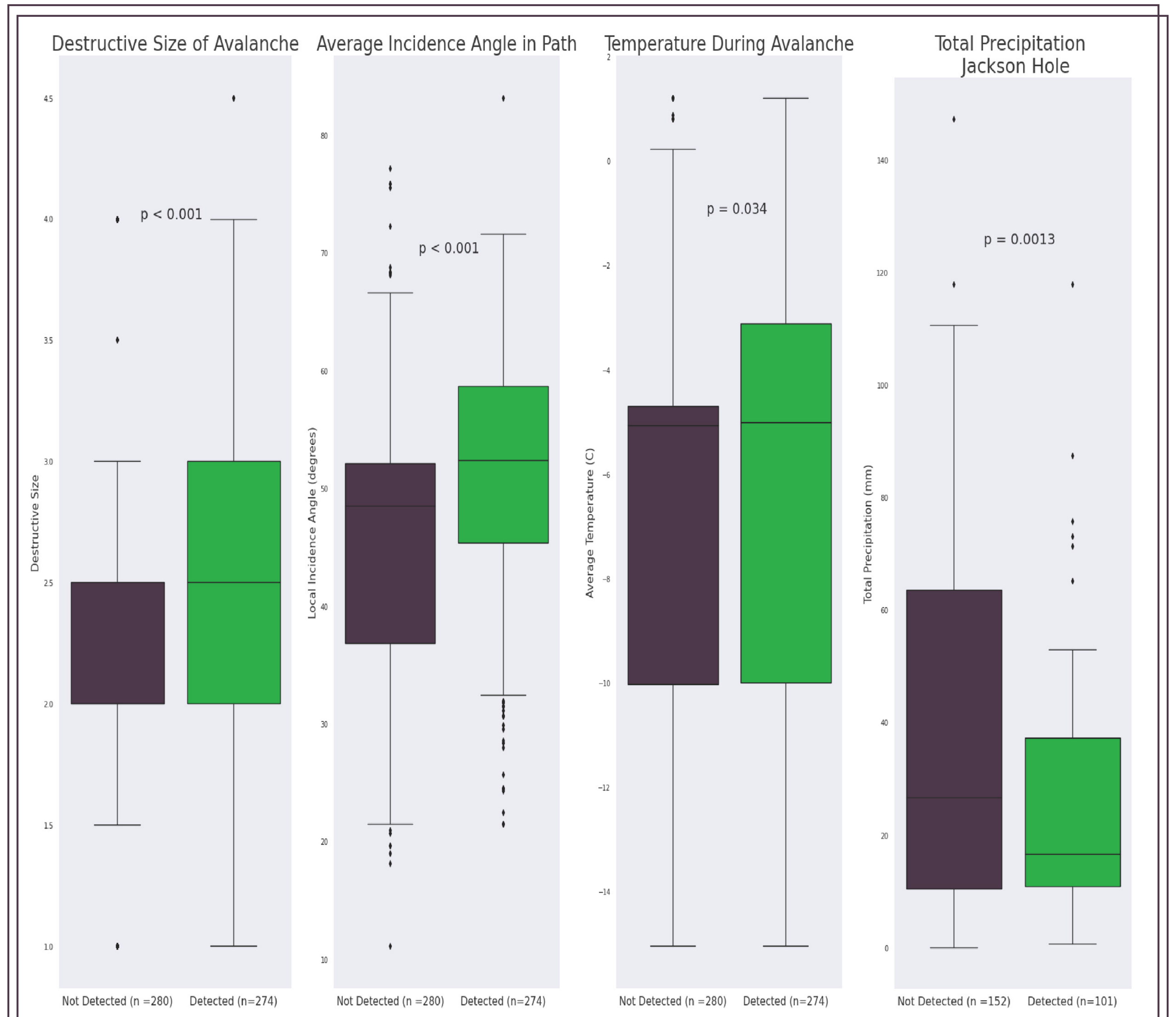

Figure 2: Selected detection factors- destructive size, average incidence angle, average temperature during the avalanche, and (for the jackson hole dataset) precipitation between the avalanche and the activity image.

- 4 major avalanche cycles were manually detected leading to 274 avalanches detected out of 554 (49.4%).
- Image pair detection rates ranged from 15.3% to 86.9%
- Destructive size, temperature during avalanche, local incidence angle, path length were all signficantly different ($\alpha = 0.05$) between detected and non-detected avalanches.
- Non-significant variables included: tree % ($p = 0.11$), maximum temperature since avalanche, average slope ($p = 0.063$), average curvature of the path.
- For the subset of Jackson Hole avalanches the additional parameter of cumulative precipitation between paths was significant.
- Chi squared analysis showed differences between natural vs artifically triggered ($p = 0.028$) and slab vs loose ($p = 0.055$) avalanches for detection, but not wet vs dry ($p = 0.28$).

Simplified Backscatter Model for Dry Snow Avalanches

To better understand the control of incidence angles on detection rates we need to first present the current model of backscatter contributions from avalanched debris (Figure 3).

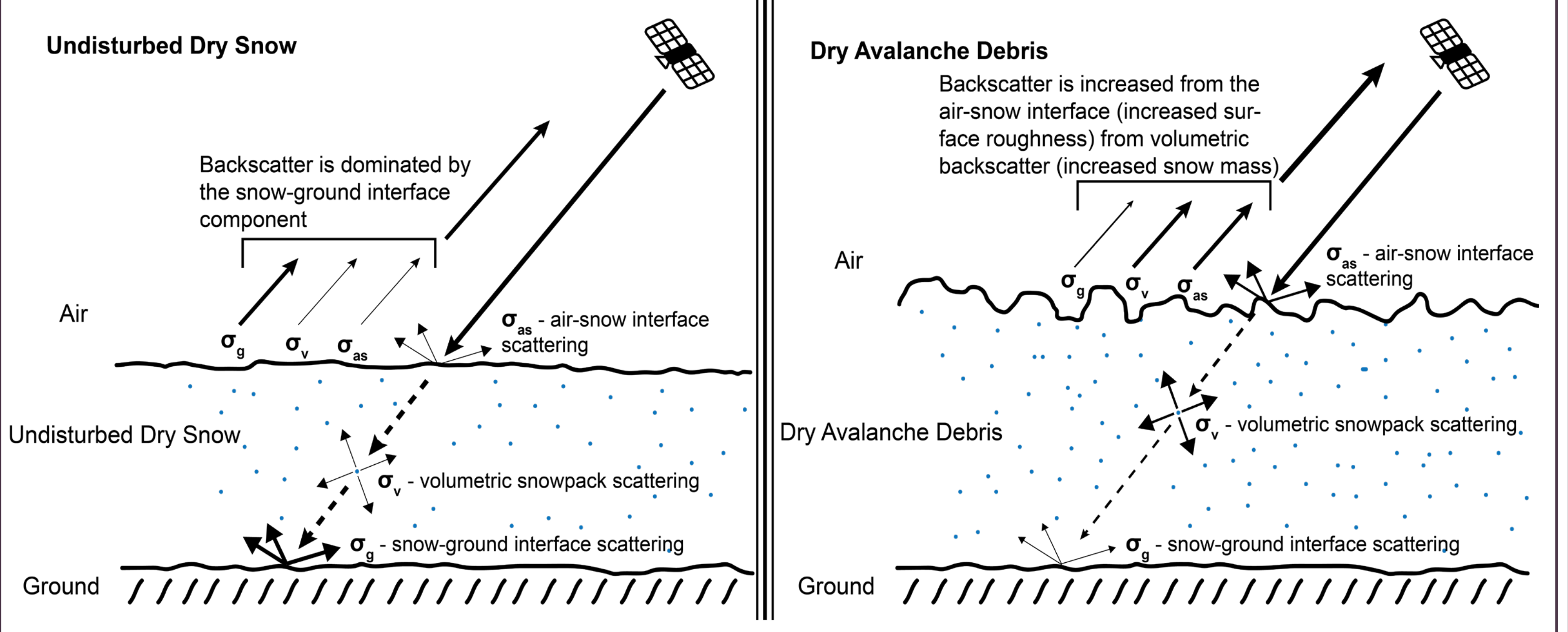

Figure 3: Simplified model of radar backscatter contrbutions for dry avalanche debris. Increases in surface roughness and snowmass are currently proposed as the primary contributors to increased backscatter for avalanche debris. Figure adapted from: Eckerstorfer and Malnes (2015).

Incidence Angle's Influence on Detection

Explaining the significant differences in local incidence angle for detected vs undetected is more challenging. Geometrically, slopes facing away from the sensor have a higher resolution, but this is probably not the full story. It has been proposed that slopes facing away from the radar should exhibit increased scattering from the rough surface of the avalanche debris and less specular reflection from the ground surface - both of which should increase the backscatter contrast of avalanche debris. Our results provide evidence for this model of backscatter contributions (Figure 4).

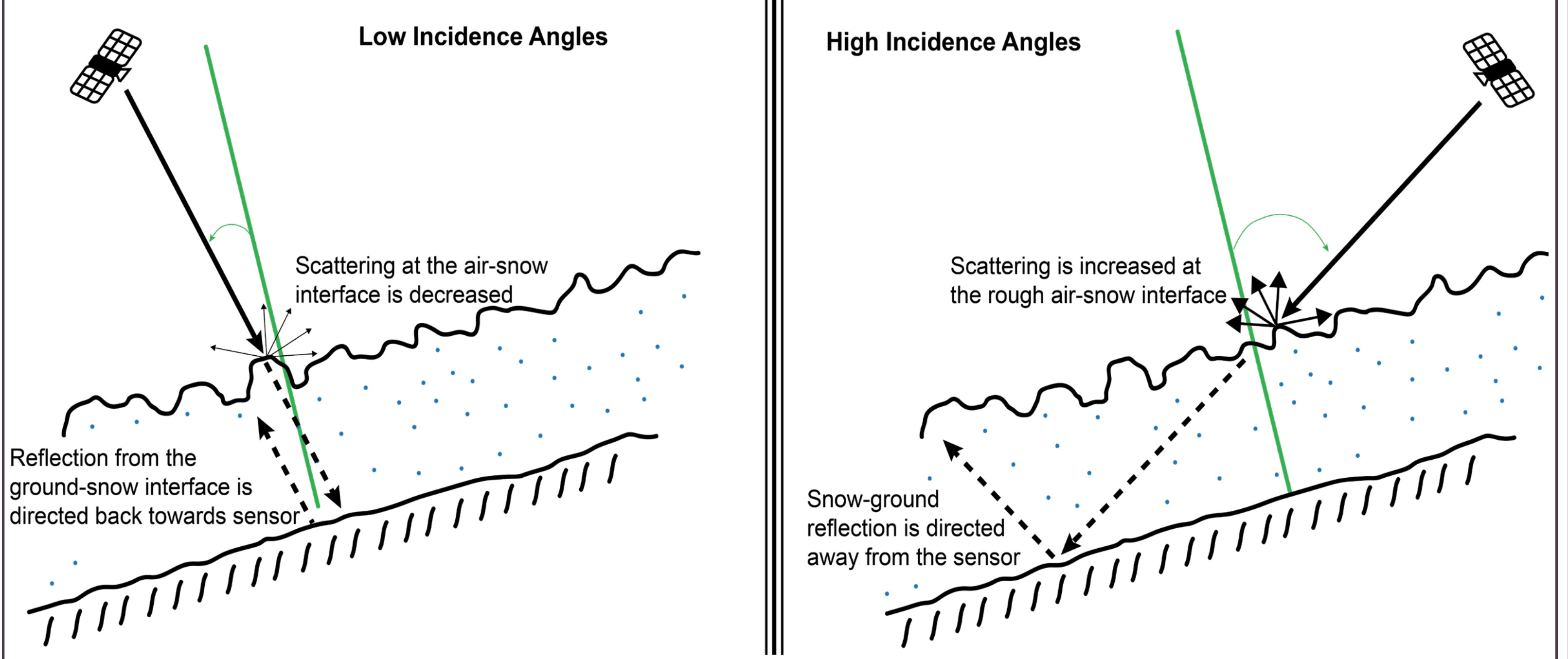

Figure 4: Idealized backscatter components for high and low incidence angles. Volumetric backscatter has been excluded for clarity.

Conclusion

- Four major cycles in Utah and the Jackson Hole region were mapped producing 274 detected avalanches and 280 undetectable avalanches.
- Primary controls on detections were: destructive size, local incidence angles, temperature during the avalanche, cumulative precipitation, and whether an avalanche was a slab or loose.
- Our observed strong relationship between detection and incidence angle provides evidence for the currently proposed model of radar backscatter in avalanche debris.
- Future work could use these factors to help improve the performance of automated classification algorithms.