Radar-based Warning and Alarm Systems for Alpine Mass Movements

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ABSTRACT

We present two applications of Doppler radar and Ground-Based Interferometric Synthetic Aperture Radar (GBInSAR) in warning and alarm systems for alpine mass movements.
Near Zermatt, two long-range Doppler radars are used to detect snow avalanches and close the road below in real time. Local authorities have access to the data at all times, and can reopen the road from any computer or mobile device.
In the Saas Valley, ice avalanches from the glaciated northwest face of Weissmies Mountain pose a threat to infrastructure and people below. We use GBInSAR to continuously monitor ice surface velocities on this face to detect and warn of potential ice fall.
Radar technologies have proven reliable and versatile in warning and alarm systems because they can monitor large areas without the need for in-situ installations and are largely unaffected by weather.

KEYWORDS

radar; mass movements; early warning; alarm system; road safety

INTRODUCTION

Alpine mass movements like snow and ice avalanches, rockfall and landslides pose an inherent threat to villages, roads or ski resorts. In many cases, structural measures can provide long-term safety. In some cases, however, these measures are too costly, negatively impact scenery or cannot be constructed where needed. In these situations, an electronic warning or alarm system, paired with organizational measures, can significantly reduce risk of injury, fatality and damage to property. Electronic alarm systems measure an event in real-time (e.g. the avalanche velocity or flow height) and trigger an automatic response like closing a road or stopping a train before the event reaches the threatened area. Warning systems measure precursory events (e.g. the acceleration of surface movements of a rock wall that announces possible rockfall) and provide the data to local authorities and experts as a basis for decision-making (Sättele & Bründl, 2015).
Where roads, railways or ski resorts are threatened by avalanches, preventive avalanche release using explosives is a common mitigation method (Gubler & Wyssen, 2002). However, the result of blastings must be verified before reopening the threatened area. Since this can

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be difficult under darkness, fog or heavy snow fall, sensors without visibility requirement are a strong asset (Meier et al. 2010, Scott et al. 2006).
Contrary to snow avalanches, ice avalanches are predictable in some circumstances. A sharp increase in surface velocities at the unstable margin of a glacier is a clear sign of an impending icefall. The rupture time can be predicted based on a time series of surface velocity data. (Faillettaz et al., 2015). The most recent glacier catastrophe in Switzerland occurred in 1965, when two million m^3 of ice broke off from the tongue of Allalingletscher and buried the construction site of the Mattmark dam, killing 88 people (Vivian, 1966).
Doppler radars, while best known as speed traps used by the police, have been applied to measure fast processes like avalanches (Lussi et al., 2012), and are widely used to monitor eruption dynamics in volcanology (e.g. Seyfried & Hort, 1999). Ground Based Interferometric Synthetic Aperture Radar (GBInSAR) has been used to study a variety of slower processes, from landslides, (rock) glacier motion, and tidewater glacier dynamics to displacements in man-made structures (Luzi et al., 2007; Monserrat et al., 2014; Nolesini et al., 2013; Rödelsperger 2011).

We report on two radar applications where these technologies have been integrated into operational alarm and warning systems: The first detects avalanches within an area of roughly two square kilometer using Doppler radars. We show that they can significantly improve avalanche release verification and be used in an automated way to close and reopen roads to traffic in real time. The second uses GBInSAR to continuously monitor the surface flow field of a glacier, data that can be analyzed to forecast icefall events.

METHOD

Radar provides several advantages over other surveying techniques. First, it does not require sensors to be installed within the observed area, keeping both people and instrumentation out of harm's way. Second, a single radar is sufficient to monitor areas spanning several square kilometers. Third, in contrast to optical methods, radar measurements are largely unaffected by low visibility. The atmosphere is mostly transparent to radar radiation and measurements are even possible during rain, snowfall or fog.
For both types of radar systems described here, data quality is crucial for reliable operation. If an alarm system is not sufficiently reliable or accurate, it may miss an event. Requirements for warning systems are slightly less strict, depending on the expected delay between precursor and event.

DOPPLER RADAR

Radar transmits electromagnetic radiation, usually in the range of a few to a few tens of GHz. This radiation is reflected by objects in the target area. If such an object is moving towards or away from the radar, the frequency of the reflected radiation is offset from the original radar frequency. Known as the Doppler Effect, objects moving toward the radar reflect a higher frequency, while objects moving away from the radar reflect a lower frequency.

This phenomenon is commonly experienced in daily life: the sound of an approaching ambulance changes its pitch abruptly when it passes the observer. An object's velocity and direction relative to the radar can thus be calculated by comparing the transmitted and reflected signal frequencies (Figure 1A).

Gravitational mass movements like avalanches, rockfall and debris flows all move with velocities of a few meters to a few tens of meters per second and can easily be measured using Doppler radars. However, Doppler radars are sensitive to all movements within their target area. Thus, additional criteria are needed to distinguish dangerous movements from "harmless" objects in motion, like helicopters or wildlife. We have conducted an extensive field study at 8 locations in Switzerland with several Doppler radars that measure velocity, range and direction to moving targets within a field of view of 90° (horizontal) × 10° (vertical) and a range of up to 2'000 m. We have acquired more than 10 terabytes (TB) of radar raw data that contain radar signals of approximately 200 avalanches, 100 rockfall events and 1 debris flow. These data were used to develop an algorithm that reliably detects snow avalanches and rockfall events in real time. The algorithm determines avalanche location and speed, and estimates its size. It can be configured to meet local needs. For example, if there are several gullies in the radar field of view, the software can be configured to only trigger an alarm if an avalanche of a certain minimum size is detected in one or more specific gullies.

So far, four Doppler radars of this kind have been deployed in operational projects: two in Zermatt (see below), one for avalanche safety of a mountain railway, and one mounted on a Wyssen avalanche tower for the verification of artificially released avalanches.

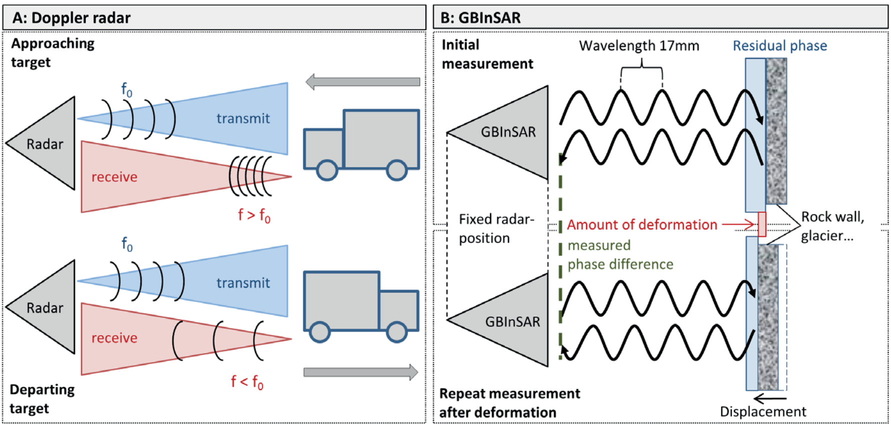

Figure 1A: Doppler radars calculate velocity and direction based on the shift in received frequency. 1B: GBInSAR systems measure deformation based on the phase shift of the received signal.

GBInSAR

Ground-based SAR interferometry is widely used to monitor slope movements (e.g. Monserrat et al., 2014; Nolesini et al., 2013), but its application to glacier motion in an operational warning system is a novelty. Similar to Doppler radar, it transmits radar radiation and analyzes the signal reflected by the target area. In contrast however, GBInSAR systems analyze changes in the phase of the reflected radiation instead of changes to the frequency. Therefore, they can measure displacements as small as 0.1 mm between two acquisitions.
The IBIS-FL radar system used in the present study works with a wavelength of 17 mm. The distance to a target is an arbitrary number of full wavelengths, plus a remaining fraction of a wavelength of at most 17 mm. If a target moves between one measurement and the next, this fraction will change, recorded as the phase shift between two measurements (Figure 1B).
An important limitation of this principle is that displacements larger than a quarter of the system's wavelength, i.e. ± 4 mm, cannot be resolved unambiguously. Furthermore, only the line-of-sight component of the displacement can be measured, and the atmosphere can cause delays that need to be corrected later. For an acquisition interval of 1 minute, the maximum velocity that can be detected is about 6 m per day. Mathematical methods (spatial phase unwrapping) can extend this limit further.
The area of coverage depends on the local terrain and the type of antenna used. The field of view of the IBIS-FL radar is roughly 60° (horizontal) × 30° (vertical) with a range up to 4'000 m. The resolution, or 'pixel size', is 0.75 m in the along-range direction and 4.4 mrad in the cross-range direction (i.e. 4.4 m at a range of 1'000 m). Details regarding the GBInSAR measurements can be found in Rödelsperger 2011.

STUDY SITES

Both study sites are situated in the southern Swiss Alps in the Canton of Valais, and were established upon request of the local authorities.

SITE 1: ZERMATT

Zermatt is one of the most famous mountaineering and skiing destinations in Switzerland, with a year-round population of roughly 6'000 and a yearly overnight stay count of about 2 million. The cantonal road between Täsch and Zermatt is the only access road to Zermatt. While most tourists travel to and from Zermatt by train, residents and commercial vehicles rely heavily on the avalanche-threatened road. Avalanches are released artificially by helicopter blasting when conditions permit. As an additional safety measure, we installed Doppler radar alarm systems on the opposite side of the valley to monitor three avalanche channels from a distance of 800-1800 m (Figure 2A). A first Doppler radar was installed in January 2015, while a second was added in December 2015 along with five traffic lights and four road barriers

The data from the Doppler radars are analyzed in real time. If our algorithm determines an avalanche is occurring, the traffic lights are immediately turned to red and the barriers are lowered to block access to the threatened sections of the road. In addition, the alarm system turns a traffic light 3 km north in Täsch to red to prevent any additional traffic from traveling up the road.

The road lies at approximately 1'600 m altitude (relative to sea level). Radar 1 watches for avalanches at altitudes of 2'100 to 2'400 m. Depending on the altitude of the release zone, and the size and velocity of the avalanches, it takes them 30-75 s to reach the road (or 100-150 s for wet snow avalanches). However, when initially detected by Radar 1, it is not yet known whether or not an avalanche will actually reach the road. This depends on a number of factors, amongst them the distribution of snow in the lower part of the avalanche channel. Because of the limited warning time, the road has to be closed temporarily. To help the local authorities reopen the road more quickly, three webcams with infrared lights were installed for night and daytime observation. After receiving an alarm as automated texts and calls to their mobile phones, authorized users can access an online platform to check the cameras and, if no debris is present on the road, remotely reopen the road. Since an on-site visit was previously required, the webcams and the remotely controlled traffic lights and

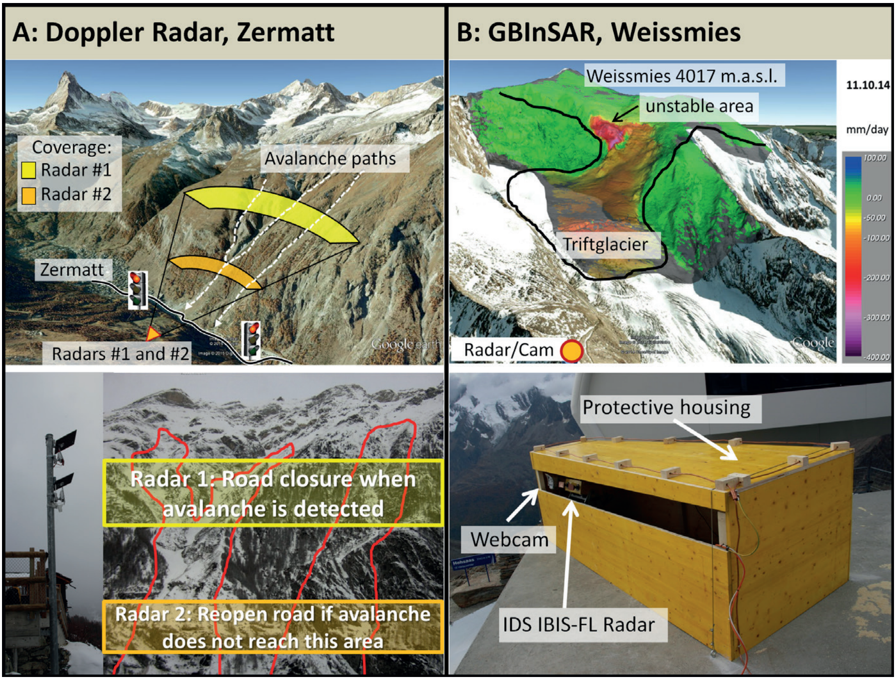

Figure 2A: Doppler radar installation near Zermatt. Radars 1 and 2 detect avalanches across the valley. Yellow/orange areas roughly indicate the radar target area. Radar 2 permits an automatic reopening of the main road. 2B: The IDS IBIS-FL ground based radar interferometer is mounted on top of the cable-car station, measuring surface flow velocities of Triftglacier at Weissmies roughly 1.5 km away.

barriers significantly shorten the time needed to reopen the road from about 45 minutes to 10 minutes.
Radar 2 was installed with the aim to simplify the reopening process even further: this radar targets an area below the field of view of Radar 1, at an altitude of 1’800 to 1’900 m. This data can be used to automatically reopen the road, since it can verify whether or not an avalanche detected by Radar 1 reached lower altitudes.
A short documentary about the system by the Swiss National TV in English can be found here: http://gpr.vn/swi

SITE 2: WEISSMIES

A large part of the glaciated northwest face of Weissmies Mountain in the Saas Valley of Switzerland recently became unstable. The likely causes of this instability are climate-induced glacier thinning of the supporting Triftgletscher and a progressive warming from freezing to melting at the ice-bed interface. Consequently, in summer 2014, a portion of the glaciated face with roughly 800‘000 m^3 of ice switched into an “active phase” with high flow velocities (Preiswerk et al., in press). Such fast flow increases the likelihood of a major icefall, which could endanger human populations and infrastructure in the Saas Valley. A monitoring campaign was initiated to detect any early warnings of dangerous break-off events to allow a timely evacuation of threatened areas. In October 2014, a GBInSAR system and a webcam were installed on the roof of the cable-car station at 3’142 m.a.s.l. (Figure 2B). The distance from the radar to the target area is roughly 1.5 km, resulting in a mean pixel width of about 6 m. The radar system operates continuously, scanning at intervals of 2 minutes. The focused raw data is uploaded to an offsite server for further analysis. While GBInSAR is not impacted by darkness or low visibility, the measurements are influenced by air temperature, pressure and humidity. Other influences include surface ablation and snow accumulation, both of which can be misinterpreted as glacier movement. Solar radiation and rain change the way the radar signal is reflected within the snowpack due to the different refractive indices of ice and water. These effects are corrected using different mathematical algorithms that consider stable reference areas. The final velocity solutions are then uploaded to a password-protected website once every hour, where they are available to glaciologists for interpretation. In addition, photogrammetric, seismic and GPS measurements have also been performed (Preiswerk et al., in press).

RESULTS AND DISCUSSION

During the winter of 2014-2015, Doppler Radar 1 recorded 32 avalanches in Zermatt, all of which were confirmed by the local authorities. Avalanches could be localized with an accuracy of 2-3° in azimuth and within a few ten meters in range (Figure 3, top left, example from Weissmies). The road was only buried twice by avalanche debris, as most avalanches stopped above the road. We have no indications or reports that the alarm system missed any avalanches. Although the system has not yet experienced extreme weather such as sleet or

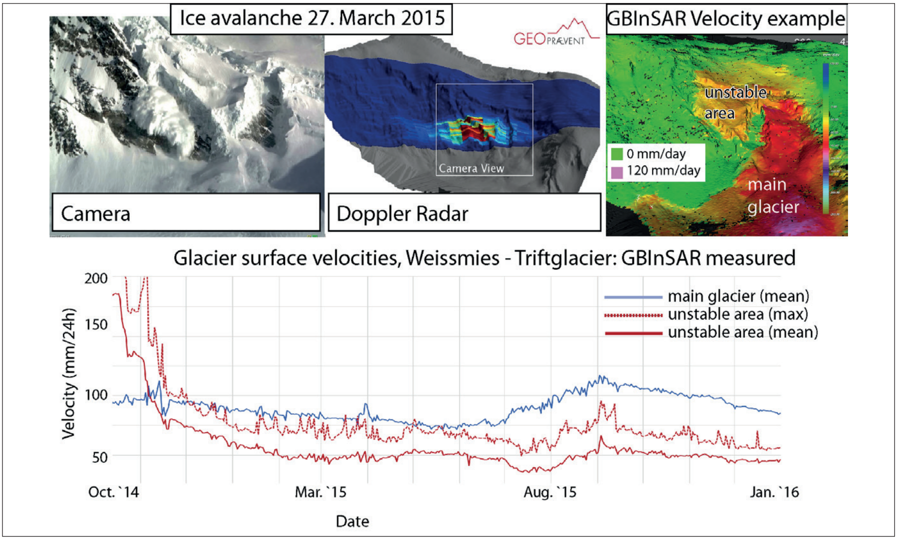

Figure 3: Top left: Ice avalanche recorded on camera and measured with Doppler radar. Top right: Example of a surface flow field on the main arm of the glacier and the unstable section. Bottom: Time series of surface velocities (averaged over the surface area) from October 2014 to January 2016.

heavy rain, it is designed to notify users once the absorption or reflection of the atmosphere rises such that the radar pulses no longer reach across the valley and back.
In 2016, between January 3 and February 15, Radar 1 detected 7 avalanches. Two of these reached the detection area of Radar 2 and triggered the alarm. All detected avalanches were confirmed by the local authorities (four of which were released artificially by blasting). At the time of writing, no false alarms have yet occurred. Avalanche sizes are detected by the radar system and can be used as an alarm criterion: during the winter, algorithms were slightly modified to avoid closing the road when only small avalanches were detected by Radar 1.
At Weissmies, glacier surface velocities were reliably estimated from the GBInSAR surface displacements over a period of over 15 months (Figure 3) and are consistent with GPS measurements (Preiswerk et al.,). The system has operated continuously since October 11, 2014, and the resulting velocity data were uploaded at least once per day on 434 of the 452 days. On the other 18 days (4% of the days), no reliable measurements were possible due to snowfall, snow drift or other difficult meteorological conditions. During the warm summer months, measurements were most reliable in the early morning, while wet snow inhibited measurements in the afternoon. The reflected radar signal remained strong enough at all times, but often decorrelated quickly under these wet-snow conditions.
The main glacier velocity showed some seasonal changes, and the unstable area slowed down from roughly 20 cm/day in October 2014 to 5 cm/day by early spring 2015. Small ice fall events of a few 1’000 m^3 occurred about once per month. Except for a few very small failures, they were preceded by a 50-200% increase in local surface velocity. The five largest events

had volumes of around 10’000 m³. We could successfully predict their time of failure one to a few days in advance by manually analyzing the velocity time series. We did not observe locally increasing surface velocities that did not lead to ice avalanches.

SUMMARY

Radar is a very versatile and robust technology for monitoring mass movements and early warnings of rupture phenomena like landslides and rock or ice avalanches. It can precisely locate the moving areas within a large field of view and measure velocities that are orders of magnitudes apart: from millimeters to meters a day with GBInSAR to many meters per second with Doppler radar. The measurements can be performed remotely, without accessing the area under observation, and are largely unaffected by weather conditions.

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