ALL-WEATHER AVALANCHE ACTIVITY MONITORING FROM SPACE?

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ABSTRACT: Information on avalanche activity or non-activity on local and regional scale is of great value for avalanche warning services, traffic authorities and experts responsible for safety in communities or ski resorts. In particular during bad weather condition, such information is available only very limited or not at all. The aim of the ESA IAP feasibility study "Improved Alpine Avalanche Forecast Service" was to investigate existing technology to overcome this gap. Of particular interest were radar-based techniques that have the potential to operate independently of daylight and weather conditions.

For testing the observation of avalanche activity on a local scale, a terrestrial radar was installed at the WSL Institute for Snow and Avalanche Research SLF, illuminating the Dorfberg close to Davos, Switzerland during winter 2013/2014. On that slope, frequent natural as well as artificially triggered avalanches can be expected. The system acquired datasets at minute temporal resolution, which allows the production of coherence maps to detect avalanche events and also features such as snow creep and free-riders tracks. The spatial coverage of the terrestrial system was 6 km$^2$ for this experiment. On the regional scale, data from radar satellites with very high spatial resolution (< 3 m) were analyzed. A TerraSAR-X stripmap mode satellite frame, for example, covers 1500 km$^2$ and has a temporal resolution of 11 days. A combination of terrestrial and space-borne radar sensors could be a powerful tool to map avalanche activity for different scales during any weather condition. We present first results of terrestrial and space-borne avalanche activity mapping at Davos during the winter 2013/2014 and discuss capabilities and limitations for local and regional avalanche warning services.

KEYWORDS: Remote sensing, avalanche forecasting, user requirements, satellite data, terrestrial radar, space-borne SAR.

## 1. INTRODUCTION

Alpine natural hazards such as debris flows, landslides, rock falls and snow avalanches threaten people and infrastructure in many mountainous regions of the earth. In the European mountains fatal snow avalanches are relatively rare events, but in Switzerland they cause more fatalities than any other natural hazard. On average 22 persons die in snow avalanches per year, mainly during snow sport activities (Techel and Darms, 2014). Considerable efforts have been made in the past decades to reduce the loss of lives and the damage to infrastructure caused by avalanches. Today, a number of technical measures, such as the installation of avalanche protection structures and the maintenance of protection forests, provide a high level of safety for vulnerable infrastructure and residential areas in the Alps. However, avalanche forecasters and snow safety experts have limited information available on the most important parameters concerning avalanches and avalanche formation. Gaps exist in particular concerning the state and development of the regional snow cover stability and avalanche activity. In the last decade, pioneering investigations using remote sensing systems (e.g. Bühler et al., 2009; Dozier and

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Painter, 2004; Larsen et al., 2011; Lato et al., 2012; Nolin, 2010; Solberg et al., 2009) or communication and positioning technology (e.g. Harvey, 2006; Strout et al., 2008; Suter et al., 2010), show the potential of satellite based technologies for snow and avalanche monitoring.

The project "Improved Alpine Avalanche Forecast Service" (AAF) was initiated by the European Space Agency ESA in September 2013 as a one-year feasibility study to investigate the potential of satellite technology to improve avalanche warning in Europe (cf. Integrated Application Program IAP, http://artes-apps.esa.int/). The project consortium consists of four partners: WSL Institute for Snow and Avalanche Research SLF, Switzerland is the project leader. The Norwegian Geotechnical Institute NGI, Norway, contributes with experience in customer-tailored avalanche warning services in Norway and a background in applying satellite technology for snow-related measurements. GAMMA Remote Sensing AG, Switzerland, and ENVEO IT GmbH, Austria, are technical consortium members with long-term experience in remote sensing of snow.

The main goals of the AAF project are a) analysis of user needs and the requirements in avalanche forecast services, b) the assessment of the state-of-the-art concerning satellite technology for snow and avalanche applications and c) the identification and testing of potential solutions to satisfy the previously identified user needs.

We investigate how existing satellite technology can be joined with ancillary information and be combined into a tailored service to support avalanche warning services and further key users in Europe. This article presents the most important results of this feasibility study.

## 2. ANALYSIS OF USER NEEDS AND GAPS

As a first step of the study the different user- and stakeholder groups in Europe as well as their needs and requirements were identified. We then focused on the identified crucial gaps in today's avalanche warning services and in defining specific demands, thus establishing the base for potential integrated solutions. By conducting interviews with experts from the avalanche warning services of NGI and SLF, a list of potential stakeholders and user groups was compiled. To validate the user group identification we consulted different experts from all European Avalanche Warning Services (EAWS) member institutions and asked for identification of their key users and customers on a local and regional level.

Three main groups were identified:

**National and regional avalanche warning services** provide regular and operational avalanche forecasts, reports and warning products on a regional or national geographic scale. The national and regional warning services are subdivided into two groups, the services with a dense (to very dense) observation and measurement network and those with a comparably thinner (partly much thinner) network.

**Alpine services** are rather diverse users, such as the local or regional avalanche commissions, road and forest administrations, power suppliers or construction companies. They operate on a regional or local geographic scale and are either privately or publicly financed.

**The general public** describes the large group of the individual or organizational end users. Residents and tourists, backcountry users and free-riders have a specific interest in the information and products of the avalanche warning services on a local scale.

A user workshop (UW) was held in November 2013 at SLF to identify the major information gaps in current avalanche warning operations in Europe and the specification of critical constraints. Representatives of 65 institutions were invited to the workshop. Finally, a total of 17 representatives from seven countries attended the workshop, including eight members of national avalanche warning services and nine representatives of the alpine service sector. Individuals or organizations from the general public were not invited because we focused on operational avalanche warning services.

The identified key problems are related to data sources, data access, and data quality. The three most important gaps identified by the users are:

**a) avalanche activity**

**b) snow surface information**

**c) snow pack stability**

Further gaps exist in the density of the observation network, information about isothermal crusts, snowdrift, gliding snow and tracks of skiers or animals. The required coverage, temporal and spatial resolution and the needed service reliability vary considerably between the different users.

For the system definition, we focused on solutions for avalanche activity mapping at the local and regional scale and on deriving regional-scale snow surface information.

## 3. POTENTIAL SERVICE OUTLINE

An integrated modular system (Fig. 1) is defined for a potential AAF service. Based on the user requirements and the state-of-the-art of available technologies, the following remote sensing technologies were identified as the most promising solution to close the gaps listed above:

a) Terrestrial Radar Interferometry (TRI), for example the Gamma Portable Radar Interferometer (GPRI)

b) Very High Resolution (VHR) SAR Earth Observation (EO) data

c) High or medium resolution (HR/MR) optical EO data

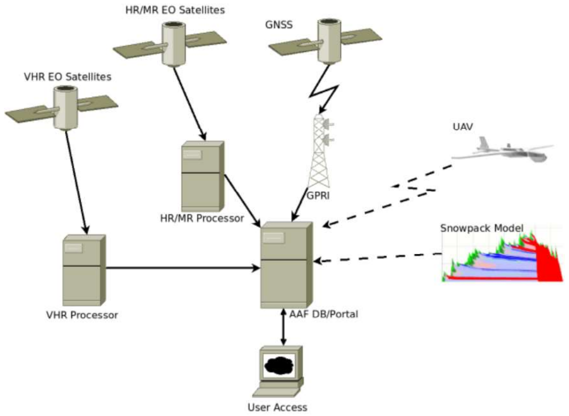


Fig. 1: Diagram of the AAF Integrated Solution. Solid lines connect modules selected for the AAF service. Dashed lines indicate optional connections with potential system modules.

We suggest the combined application of satellite-based synthetic aperture radar (SAR) technology and terrestrial radar interferometry (TRI) as the most promising solutions to monitor avalanche activity. Medium and high resolution optical and radar satellite data are used to derive snow surface information such as snow covered area (SCA) or snow surface wetness over larger areas. Future modules of the system could be webcam images, imagery from unmanned aerial vehicles (UAV) and snow pack information derived from physical snowpack models such as Snowpack (Lehning et al., 1999) or Crocus (Brun et al., 1989).

The modules provide information in a generic way so that they can easily be imported into a service database portal (AAF DB/Portal, Fig. 1). In order to test the described AAF service the Common Information Platform for Natural Hazards in Switzerland (**G**emeinsame **I**nformationsplattform **N**aturgefahren, GIN) was selected (http://www.gin-info.ch/gin_short_en.htm). The service can be adapted and integrated in any existing portal installed at the users' end. As existing users are familiar with their own portal, this grants an easy information access by the users, and increases the chances for the AAF service to be accepted as a source of additional information.

## 4. TERRESTRIAL- AND SATELLITE-BASED RADAR DATA

### *4.1 Terrestrial Radar Interferometry (TRI)*

The 17.2 GHz (Ku-Band) Gamma Portable Radar Interferometer (GPRI, Fig. 2) can map key slopes with very high temporal resolution (30 seconds – 1 minute) even under bad weather conditions and during nighttime. The GPRI has a measurement range from 50 m to 18 km. The range resolution is 1 m per pixel and the horizontal resolution is 8 m at a distance of 1 km. The device is highly sensitive to small changes (~1 mm) in the snow surface. In order to protect the GPRI from environmental impact (e.g., from winds up to 150 km/h), it is sheltered with a radome as shown in Fig. 2.

Fig. 2: Gamma Portable Radar Interferometer (GPRI) with a height of about 2.2 m and a weight of 45 kg, installed in a radome at SLF.

### *4.2 Satellite SAR data*

Satellite-based radar data can be acquired independently of daylight and weather conditions. By comparing a temporal sequence of data, changes of the ground surface such as snow avalanches can be detected with relatively high spatial resolution (better than 3 m). The AAF SAR data processors can receive SAR data from different satellites, such as TerraSAR-X, Cosmo/Skymed, and Radarsat-2. It produces orthorectified avalanche activity maps in GeoTIFF format.

For this feasibility study the following **VHR SAR** satellites were tasked:

- TerraSAR-X (Liao, 2007)
- Risat-1 (Misra et al., 2013)

Further potential satellites would be Cosmo/Skymed, Radarsat-2, Kompsat-5, and the future satellites PAZ and Sentinel-1.

The following **HR/MR optical** satellites were selected for deriving snow surface information:

- Daily Terra MODIS (Moderate Resolution Imaging Spectroradiometer) data with 250 m to 1 km pixel size, provided by NASA free of charge on a web server
- Landsat-8 OLI/TIRS (launched in 2013) with 15 m to 100 m pixels size (depending on the spectral range) and 16 days repeat time interval, provided by U.S. Geological Survey free of charge

Further potential satellites would be Suomi-NPP VIIRS and the future Sentinel-3 for medium resolution, and SPOT-5/-6 and the future Sentinel-2 for high spatial resolution optical data.

For processing HR and MR optical satellite data, and for deriving statistical snow information related to particular terrain conditions, digital elevation models (DEM) and their derivatives products for slope and aspect (with the same resolution as the satellite data) are mandatory. Additionally, surface types as water bodies or forests are masked in the fractional snow cover maps (Nagler et al., 2010).

## 5. TEST SITE

The Dorfberg slope close to Davos, Switzerland, was selected as the main site to test the proposed integrated system. The southeast-facing slope opposite the SLF institute building ranges from 1560 to 2536 m a.s.l. Due to its steep inclination (most parts are steeper than 30°) the slope faces regular avalanche activity. The GPRI was positioned close to the SLF building at 1560 m a.s.l. and observed an area of about 6 km² up to an altitude of 2640 m a.s.l. GPRI data from the Dorfberg test site were acquired from 31.1.2014 until 24.4.2014. The instrument was remotely accessible through an internet connection. Additionally, data from the following instruments were available for the test site to validate the products from the GPRI (Fig. 3):

- Webcam, taking pictures every two minutes, operating during the whole winter period
- Automatic weather stations: Weissfluhjoch (WFJ, 2540 m a.s.l.), SLF Flüelastrasse (SLF, 1560 m a.s.l.) and Dorfberg (DFB, 2140 m a.s.l)., operating continuously

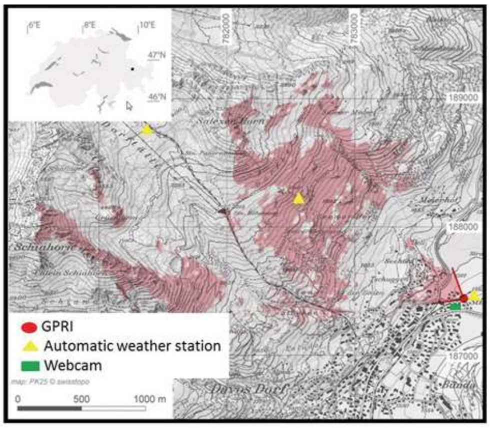


Fig. 3: Map of the instrument locations and visible target area of the GPRI (areas shaded in red).

## 6. RESULTS

### *6.1 Avalanche activity mapping with Terrestrial Radar Interferometry*

The GPRI scanned the Dorfberg at different time intervals between 1 and 15 minutes. Mechanical changes in the snow surface induced by, e.g., avalanches lead to a drastic reduction of the temporal coherence. Because vegetation shows this effect even faster due to wind, we masked out areas with dense vegetation to prevent false results. Interferometric processing and post processing of the coherence map, using adaptive filtering to enhance the morphology of the decorrelated area and, thereby, enhancing the detectability of fast decorrelation events was performed on the instrument itself. Georeferencing of final data products was done off-instrument. The on-site processing has already been successfully tested earlier but was not applied to allocate memory for fast acquisitions. The transfer of automatically selected final products, such as warning messages based on thresholds, is possible in near-real time.

GPRI data can be used to produce, amongst others, timely avalanche activity maps at very high temporal and spatial resolution depending on target distance and slope. The radar can also produce images when the optical webcam is blinded by clouds and during night. Strong wind drift of snow in the target area leads, on the other hand, to a drastic reduction of coherence within short time spans. This can reduce the reliability of the avalanche identification.

The availability of coherent acquisitions in short time intervals of minutes allows deriving displacement information from the interferometric phase. This permits insight into dynamic processes in the snow cover that sometimes result in an observed avalanche. The GPRI instrument runs in continuous monitoring mode and provides selected products such as a coherence based avalanche map (Fig. 4), free-riders track maps or snow creep maps based on phase stacking (Fig. 5). To get an overview on the areas with snow creep, daily maps were produced indicating the total displacement observed during the previous day.

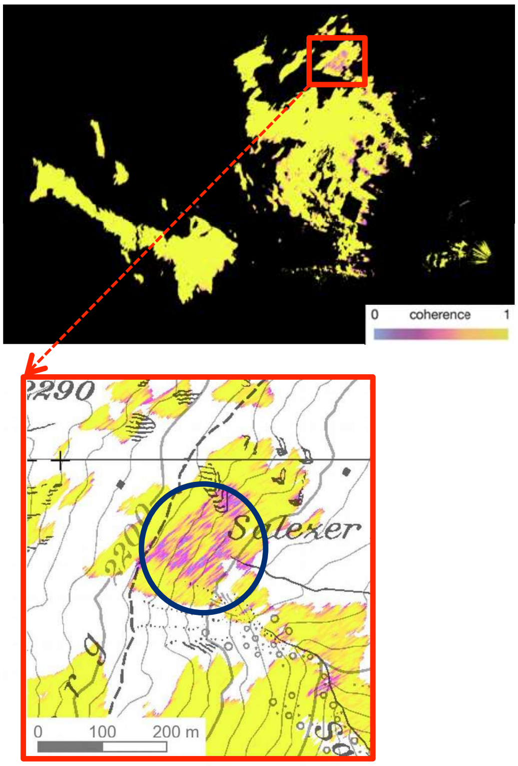


Fig. 4: Top: Coherence avalanche map. Overview of 2014-02-23 from 11:00 to 11:05 hours. Bottom: Detail of a sudden spatially localized coherence loss (cycle) caused by an avalanche event.

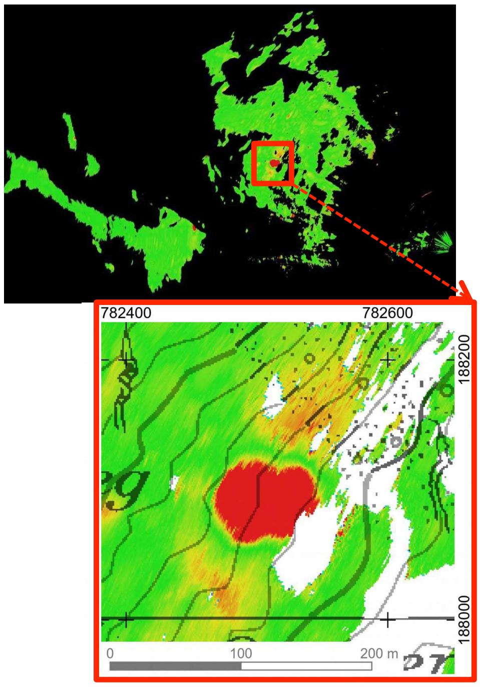


Fig. 5: Top: Daily total displacement map of 2014-03-11. Bottom: Example of a daily cumulative line-of-sight displacement map, color-codes : green = 0 cm, red >= 5 cm.

### *6.2 Avalanche mapping with VHR SAR data*

Data were downloaded and processed to orthorectified backscatter images using the GAMMA software (www.gamma-rs.ch). In order to make changes in the snowpack more visible, change detection techniques were applied and color composites produced (Fig. 6).

Avalanche mapping using VHR SAR data is based on change detection technologies applied on the back scattering information of data acquired on different dates. Unfortunately, ten of sixteen ordered satellite data acquisitions were cancelled due to conflicts with other satellite customers. Only two TerraSAR-X data sequences were available for processing and interpretation:

- *Descending : 23.1.2014 – 25.2.2014*
- *Ascending: 26.1.2014 – 17.2.2014 – 28.2.2014*

The analysis of the available data sequences showed no indication for avalanches at the

Dorfberg. But we were able to identify avalanche activity in nearby areas such as the Pischa valley (Fig. 6).

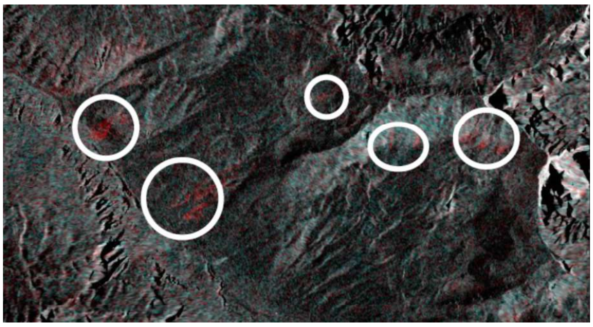

Fig. 6: Extract of composite 25.2.2014 (red) and 17.1.2014 (green) covering the Pischa valley, north of Davos. White cycles indicate fresh avalanches.

### 6.3 *Validation of Avalanche Mapping*

The validation of the terrestrial radar products was done on a visual basis by comparing the results with the webcam-images (Fig. 7).

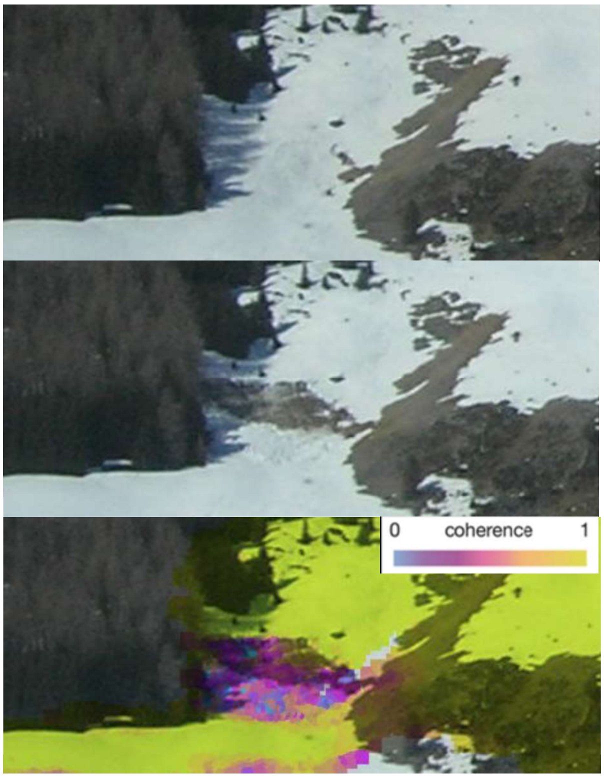


Fig. 7: Top: Webcam at SLF 2014-03-08, 11:32.
Middle: Webcam: 2014-03-08 11:36
Bottom: Avalanche coherence map 2014-03-08 11:34 – 11:36.

In order to compare the outcome of the GPRI-campaign with the webcam-validation, the data had to be transposed in the same reference frame. The validation for the avalanche mapping using VHR SAR data was planned with visual observations of the Dorfberg webcam. Since we couldn't find any avalanches at Dorfberg, but some in the Pischa Valley, we used information from the IFKIS (Intercantonal Early Warning and Crisis Information System) database for validation. IFKIS provides information about the avalanche size (small, medium, large) but not about avalanche type. We find that avalanches are successfully identified if the SAR observation geometry is good (no shadow or layover), the avalanche is larger than a few image pixels and if the deposit has a certain thickness (Fig. 6). Some of the identified avalanches are not present in the IFKIS database, even though we are convinced that the observed features actually are avalanches. We hypothesize that this is due to the fact that the field observers are not able to map all events.

### 6.4 *Snow extent mapping by means of HR/MR EO data*

Daily Terra MODIS data are used for the generation of fractional snow cover maps with 250 m pixel size over the entire Alpine region and neighboring lowlands. The multi-spectral unmixing procedure with end-member selection (Shi, 2001) was further developed by ENVEO (Nagler et al., 2010) for high alpine, un-forested terrain, and is used for mapping fractional snow cover. Snow in forests is classified binary (Hall et al., 2002). The processing line, illustrated in Fig. 8, is fully automated, and products are provided within six hours after image acquisition. Fig. 9 shows an example of the daily fractional snow cover map from MODIS data with clear sky conditions, covering the European Alps and neighboring lowlands.

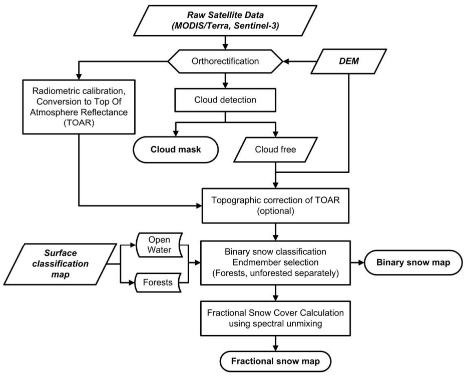


Fig. 8: Flowchart of mapping fractional or optionally binary snow cover from optical satellite data.

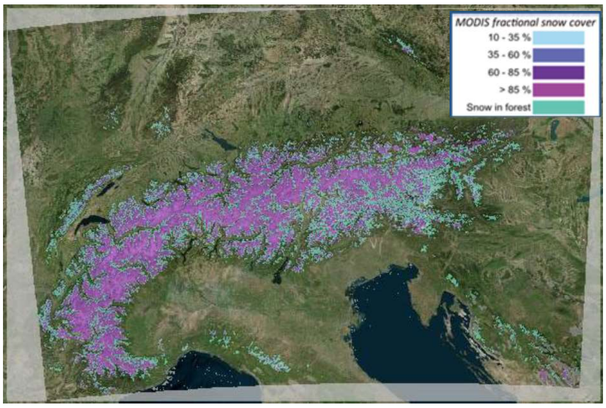


Fig. 9: Fractional snow cover (FSC) map over the Alpine area from MODIS data on 9 March 2014. The product provides fractional snow cover information in percentage. For visualization issues the FSC product is classified in four FSC ranges, as indicated in the legend. Additionally, binary snow in forest is shown as a separate class.

For more detailed information within particular areas of interest identified by users, statistical information of the fractional snow cover in dependence on altitude or local aspect can be provided.

Snow surface classification from high resolution optical satellite data is based on the same procedure, and has been performed for selected Landsat-8 scenes acquired in the winter season 2014 with clear sky conditions over the test site Davos. The spatial resolution of these satellite data provides an added value. However, the long revisit time of such satellites and the frequent occurrence of cloud cover, hiding potential areas of interest, reduce the usability of currently available high resolution satellite data for an operational service.

The applied method for mapping fractional snow cover from optical satellite data is mature. Accuracy assessments have been performed in several national and international projects, and are continuously ongoing. The root mean square errors of the derived fractional snow cover information per pixel from MR and HR optical satellite data usually range between 10 – 30 %.

## 7. CONCLUSION AND OUTLOOK

The main goal of the AAF study was the development of a solution filling the most important gaps identified by users, which are:

a) avalanche activity mapping,

b) snow surface information

c) snow pack stability.

Terrestrial and space-borne radar sensors are promising tools to improve avalanche warning services. With GPRI data the local mapping of avalanche events is possible even for avalanches with small spatial extents of a few tens of meters, independent of weather conditions or daylight. The on-site processing of final maps is possible in near-real time. However, only single key slopes can be covered and strong wind-drift or free-riders tracks can cause similar decorrelation signatures as avalanches.

Very high spatial resolution SAR data is successfully applied to map medium and large avalanche events independent of weather and daylight over large areas (> 1000 $km^2$). However, small avalanches are difficult to detect and data processing has to be optimized. Data availability and data costs turn out to be the main problems hampering an economically feasible service today.

Snow surface information, including fractional snow cover maps and snow distribution with respect to local altitude and aspect are successfully derived daily from medium resolution optical satellite data for the whole alpine area, and monthly from high resolution optical satellite data for particular areas of interest. Daily medium resolution optical satellite data are already used for operational services providing snow surface information with 250 m pixel size. For optical satellite data the frequent occurrence of cloud cover is the main drawback. For high resolution satellite data the revisit time, which is in the order of two to four weeks, significantly reduces the option to provide an operational service based on such data.

We identify four main issues to be solved in order to set up an economically feasible operational service which is valuable for the avalanche warning community:

- Reliability of data access has to be improved significantly (satellite SAR data).
- Temporal resolution of satellite data has to be better than 3 days.
- Costs for high resolution satellite data have to be reduced.
- The willingness-to-pay and/or the available budgets of potential user are presently too low for an economically successful service.

We plan a small follow-up research project in Switzerland for the winter season 2014/15 focusing on GPRI product generation for traffic infrastructure safety applications.

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Landsat data available from the U.S. Geological Survey.

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