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Remote Sensing of Permafrost-related Problems and Hazards

Andreas Kääb^{*,†}

Department of Geosciences, University of Oslo, Oslo, Norway

ABSTRACT

Modern remote sensing techniques can help in the assessment of permafrost hazards in high latitudes and cold mountains. Hazard development in these areas is affected by process interactions and chain reactions, the ongoing shift of cryospheric hazard zones due to atmospheric warming, the large spatial scales involved and the remoteness of many permafrost-related threats. This paper reviews ground-based, airborne and spaceborne remote sensing methods suitable for permafrost hazard assessment and management. A wide range of image classification and change detection techniques support permafrost hazard studies. Digital terrain models (DTMs) derived from optical stereo, synthetic aperture radar (SAR) or laser scanning data are some of the most important data sets for investigating permafrost-trelated mass movements, thaw and heave processes, and hydrological hazards. Multi-temporal optical or SAR data are used to derive surface displacements on creeping and unstable frozen slopes. Combining DTMs with results from spectral image classification, and with multi-temporal data from change detection and displacement measurements significantly improves the detection of hazard potential. Copyright © 2008 John Wiley & Sons, Ltd.

KEY WORDS: permafrost; remote sensing; hazard; risk; disaster

INTRODUCTION

A number of potential environmental and socioeconomic impacts of atmospheric warming in high latitudes and cold mountains are associated with permafrost (Haeberli, 1992b; Burger *et al.*, 1999; Haeberli and Burn, 2002; Nelson *et al.*, 2002; Johnson *et al.*, 2003; Harris, 2005; Kääb *et al.*, 2005b). Permafrost-related threats include floods, mass movements, thaw and frost heave. Combinations and chain reactions of these and other processes may lead to severe permafrost-related problems or even disasters. In addition, severe problems may arise from indirect threats, such as adverse effects on water availability, traditional subsistence practices, tourism and related socio-economic consequences (e.g. Burger *et al.*, 1999; Nelson *et al.*, 2002; Ford and Smit, 2004), or at a global scale, problems such as methane emission from thaving permafrost.

In this contribution, the following terms are used (JTC1, 2004): *threat* is a 'natural phenomenon that could lead to damage, described in terms of its geometry, mechanical and other characteristics. The threat can be an existing one (such as a creeping slope) or a potential one (such as a rockfall)'. *Susceptibility* is the spatial distribution of threats (sometimes referred to as hazard disposition). *Hazard* is the 'probability that a particular threat occurs within a given period of time'. Threat therefore describes the process and magnitude of a dangerous event, susceptibility includes its spatial distribution and hazard its temporal distribution. *Vulnerability* is the 'degree of loss to a given element, or to a set of elements within the area affected by a hazard', or to a 'set of conditions and processes resulting

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^{*} Correspondence to: Professor Dr Andreas Kääb, Department of Geosciences, University of Oslo, PO Box 1047 Blindern, N-0316 Oslo, Norway. E-mail: kaeaeb@geo.unizh.ch

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from physical, social, economic, and environmental factors'. *Risk* is a 'measure of the probability and severity of an adverse effect to life, health, property, or the environment'.

Assessment and management of permafrost hazards require the application of modern integrative earthobservation techniques for a number of reasons. Permafrost threats commonly occur in remote regions, which are difficult or dangerous to access. The vast areas of interest, potential process interactions and chain reactions, and the great reach of some of the threats (e.g. floods) require sensors capable of covering large areas simultaneously.

Climate change induces disturbance in permafrost conditions and can alter hazard processes, probabilities and magnitudes so that experience, which is based on historical events at a given location, is no longer sufficient for hazard assessment. In addition, human settlements and activities increasingly extend towards dangerous zones. As a result, historical data have to be combined with new observation and modelling approaches. Due to rapid change in the cryosphere, hazard assessments should be undertaken routinely and regularly, and must be combined with continuous monitoring. Remote sensing is particularly well suited for both regular and rapid observation.

Recent developments in airborne and spaceborne remote sensing have opened up new possibilities for the assessment of natural hazards in general (Mantovani et al., 1996; Singhroy et al., 1998; Ostir et al., 2003; Metternicht et al., 2005; Tralli et al., 2005; Delacourt et al., 2007) and permafrost-related hazards in particular (Duguay and Pietroniro, 2005; Kääb, 2005b; Kääb et al., 2005a; Quincey et al., 2005). Kääb et al. (2005a) and Quincey et al. (2005) provide overviews of remote sensing methods applied to glacier hazards and the former also includes hazards related to mountain permafrost. Several review papers focus on the remote sensing of landslides, and these generally refer to the involvement of permafrost in slide processes (e.g. Metternicht et al., 2005; Delacourt et al., 2007). Stow et al. (2004) and Duguay et al. (2005) review remote sensing methods for lowland permafrost.

The aim of this paper is to provide the first integrated overview of remote sensing of hazards and problems relating to both lowland and mountain permafrost. Important aspects of the remote sensing of geohazards are examined, spaceborne, airborne and terrestrial remote sensing methods for geohazard assessment are summarised, and analyses in the spectral, geometric and multi-temporal domains of remotely sensed data are presented. Remote sensing applications for specific permafrost hazards and problems and for early warning and disaster management are described. The final section of the paper examines prospects for the future.

REMOTE SENSING DATA ACQUISITION METHODS

This section describes remote sensing methods that potentially can be used for permafrost hazard management. Their application is discussed in more detail in the later sections. For an explanation of sensor acronyms, see Table 1.

Characterisation of Remote Sensing Systems

The applicability of remote sensing to permafrost problems and hazards is governed by the following characteristics of a remote sensing system:

The *spatial resolution* of the sensor determines the detail that can be extracted from the data. Fine resolution is generally required to assess permafrost threats, problems and disasters, because the objects observed are often small and fine details can be critical for a sound hazard assessment. Spatial resolution can be expressed as high ($<5 \text{ m} \times 5 \text{ m}$ pixel dimension), medium (5–100 m), low (100–1000 m) and very low (>1000 m).

The *spatial coverage* is the area or width of the ground track sensed and is roughly related to the spatial resolution of the sensor because of technical constraints, such as sensor sensitivity and onboard-recording and down-link capacities. Medium-resolution Landsat, IRS and ASTER data, for example, are useful for initial regional-scale hazard assessments. High-resolution airborne imagery, laser scanning, CORONA, Ikonos, QuickBird, PRISM or SPOT5 data are preferable for detailed local-scale investigations, but usually cannot be applied over large areas due to high costs and small spatial coverage.

The *temporal resolution* is the revisit time of the remote sensing system. For assessments of hazards, the temporal resolution has to be consistent with the rate of hazard development or the changes to be observed. The temporal resolution of a system is a function of the platform type (spacecraft, aircraft, ground installation), the system's spatial coverage, the airborne or terrestrial accessibility of the study area and how far the sensor can be rotated in cross-track direction. The AVNIR-2 sensor onboard the ALOS satellite for example can be pointed up to $\pm 44^{\circ}$ allowing for repeat imaging as frequently as 24 h on average. Annual resolution may be sufficient to

monitor the development of thaw lakes, whereas repeat times of a few days are required for disaster management in connection with landslide-induced temporary lakes.

The *timing of data acquisition* must be under the control of the user, or meet the user's needs by chance. The probability of the latter occurring increases with temporal resolution. Timing is of particular importance when remote sensing data are required at a given repeat cycle such as for early warning purposes, when seasonal restrictions limit suitable observation periods, or when rapid response is needed for search-and-rescue operations and disaster management.

The portion of the electromagnetic spectrum available to the sensor determines the surface parameters that are recorded and the dependence of the sensor on weather and illumination conditions. For example, microwave sensors can gather data in all weather conditions and at night, and thermal infrared sensors have a night-time capability, whereas optical sensors cannot be used during darkness or through cloud cover. This limitation can be crucial, for example, in winter in high latitudes, or for areas and seasons with frequent cloud cover.

The *stereo, interferometric or ranging capability* of the remote sensing system enables computation of three-dimensional target positions and terrain elevations. This capability is commonly a prerequisite for analysing landslide hazards in the absence of pre-existing appropriate topographic data.

The *usefulness of data* refers to the degree that remotely sensed data can be applied to hazards and disasters, for example access to data archives, speed of on-demand acquisition, speed of delivery, simplicity of data formats and size, data costs, availability of hardware and software, and the user's processing and analytical knowledge. These factors are still frequently bottlenecks in the application of remote sensing to permafrost-related hazards and problems.

Spaceborne Methods

Satellites, space shuttles and the International Space Station have been used as spaceborne platforms for remote sensing sensors. Spaceborne remote sensing technologies suitable for permafrost hazard and disaster management include the following (see Table 1):

Multispectral and panchromatic spaceborne imaging in the optical section of the electromagnetic spectrum (visible, VIS; near infrared, NIR; shortwave infrared, SWIR) are well-established satellite remote sensing methods for mapping and monitoring ground cover and changes related to permafrost and geohazards. Multispectral sensors have a few broad spectral bands with a typical width in the order of 0.1 μ m. The method is often used for detecting threat source areas and terrain changes, and for mapping hazard zones.

Hyperspectral imaging from space uses tens to hundreds of narrow spectral bands with a typical width in the order of 0.01 μ m. The method has not been used for permafrost-related hazards and problems to date, but it could enable spectral discrimination of surface types and changes that are barely distinguishable using multispectral remote sensing. Consideration or correction of atmospheric effects is particularly important for hyperspectral data. The experimental medium-resolution sensors Hyperion on the EO-1 spacecraft, and CHRIS on the PROBA spacecraft potentially could be used for permafrost investigations.

Thermal infrared sensors are carried on some optical spaceborne instruments, for example Landsat and ASTER. Thermal infrared data can be transformed into surface temperatures and thus are of particular interest to permafrost studies.

Microwave backscatter from active sensors, signal polarisation, signal phase and frequency, or interferometric-phase coherence using synthetic aperture radar (SAR) sensors can be analysed in the context of permafrost threats. SAR data from space platforms, together with multispectral data, are most frequently applied to permafrost and related problems, especially on an operational basis, because they cover large areas, complement optical data, and are independent of weather and sunlight.

Scatterometers, which are active microwave sensors measuring the backscatter accurately in different directions, or *passive microwave* sensors, which measure the natural microwave emissions of the Earth, are useful for global-scale studies of snow cover or sea ice cover, and hence can contribute to large-scale studies of permafrost conditions and their changes. The spatial resolution of passive microwave sensors is in the order of tens of kilometres, which is obviously too low for local studies.

Satellite optical stereo enables computation of digital terrain models (DTMs), a prerequisite for some studies of landslide threats. The method uses photogrammetric principles based on two or more overlapping images. Darkness and cloud cover are the main limitations.

Interferometric SAR (InSAR) from space can be used to derive DTMs. DTMs from the Shuttle Radar Topography Mission (SRTM), an InSAR campaign, are particularly useful for regional-scale hazard assessments in remote areas. Repeat InSAR can be

Table 1 Overview of s	paceborne remote sensing	methods used, or potenti	ally suitable for permafrost probl	em and hazard studies.
Spaceborne method	Techniques	Parameters, remarks	Selected satellites/sensors	Selected references
Mono-/multispectral imaging	Interpretation; classification Image matching	Spectral surface characteristics and changes over time Terrain displacements	MODIS (Moderate Resolution Imaging Spectroradiometer), MERIS (Medium Resolution Imaging Spectrometer Instrument), Landsat series, ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer), SPOT series (Systeme Pour l'Observation de la Terre), AVNIR-2 (Advanced Visible and Near-Infrared Radiometer, aboard the Advanced Land Observing Satellite (ALOS) spacecraft), IRS (Indian Remote sensing Satellite), QuickBird, Ikonos, Corona spy satellite	Dean and Morrissey (1988); McMichael <i>et al.</i> (1997); Lewkowicz and Duguay (1999); Ødegård <i>et al.</i> (1999); Etzelmüller <i>et al.</i> (2001); Duguay and Pietroniro (2005); Frohn <i>et al.</i> (2005); Grosse <i>et al.</i> (2007); Kääb (2005b); Hinkel <i>et al.</i> (2007)
Hyperspectral imaging	Hyperspectral classifications, spectrometry	Spectral signatures	series Hyperion (aboard the Earth Observing Mission 1 (EO-1) spacecraft) CHRIS (Compact High-Resolution Imaging Spectrometer; aboard Project for On-Board	Cutter (2006); Doggett et al. (2006); Ip et al. (2006)
Thermal infrared imaging		Thermal emissivity; surface temperatures	Autonomy (PKOBA)) Landsat, ASTER	Lougeay (1974, 1982); Salisbury <i>et al.</i> (1994); Leverington and Duguay (1997); Ranzi <i>et al.</i> (2004); Shengbo (2004); Kääb (2005b)

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Active microwave sensing	SAR, polarimetric SAR, scatterometers	Backscatter intensity; polarisation; frequency	ERS 1/2 (European Remote sensing Satellite), Envisat, RADARSAT, ALOS PALSAR (Phased Array type L-band SAR), TerraSAR-X, SIR (Shuttle	Granberg <i>et al.</i> (1994); Rignot and Way (1994); Kane <i>et al.</i> (1996); Zhen and Huadong (2000); Floricioiu and Rott (2001); Yoshikawa and Hinzman (2003); Mironov <i>et al.</i> (2005)
Passive microwave sensing		Surface temperature; soil humidity	Imaging kadar), SKLM (Shuttle Radar Topography Mission) SMMR (Scanning Multichannel Microwave Radiometer), SSM/I (Special Sensor Microwave	Kim and England (1996); Grippa <i>et al.</i> (2007)
Satellite optical stereo	Along-track, cross-track Two or more	Digital elevation models; elevation changes; terrain displacements	Imager) SPOT series, ASTER, ALOS PRISM (Panchromatic Remote Sensing Instrument for	Toutin and Cheng (2002); Kääb (2005b)
Radar interferometry	succo channels SAR interferometry; differential InSAR; permanent scatter InSAR; nSAR;	Digital elevation models; terrain displacement; surface changes; phase coherence	ouceo wapping, Quickbird, Ikonos See active microwave sensing	Moorman and Vachon (1998); Wang and Li (1999); Zhijun and Shusun (1999); Kimura and Yamaguchi (2000); Nagler <i>et al.</i> (2002); Kenyi and Kaufmann (2003); Hilley <i>et al.</i> (2004); Strozzi <i>et al.</i> (2004): Tait <i>et al.</i> (2005): Sinshrov <i>et al.</i>
LIDAR altimetry	single-pass, repeat-pass Full-waveform analysis	Elevations; surface roughness	GLAS (Geoscience Laser Altimeter System, aboard Ice, Cloud, and land Elevation Satellite (ICESat)	(2007) Ranson <i>et al.</i> (2004); Sauber <i>et al.</i> (2005)
SAR = Synthetic apertui	re radar; InSAR = interfer	ometric synthetic aperture	e radar; LIDAR = light detection	and ranging.

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applied to measure terrain displacements relating to permafrost with techniques such as differential InSAR (DInSAR) or permanent scatterer SAR.

Spaceborne light detection and ranging (LIDAR) using the GLAS instrument on the ICESat satellite provides terrain elevations for laser footprints 70 m in diameter and along-track spacing of 170 m. An increasing number of studies are proving the potential of this instrument for use in mountain topography or boreal forests, even though it was not designed for rough surfaces.

Airborne Methods

The main platforms used for airborne remote sensing are airplanes and helicopters, but unmanned air vehicles have become increasingly important. Airborne remote sensing technologies that are applicable for permafrost hazard and disaster assessments include the following (see Table 2):

Hard-copy or digital photogrammetry based on airborne frame imagery or linear array charge-coupled device sensors are well-established techniques for generating DTMs, detecting vertical terrain changes, measuring lateral terrain displacements, and interpreting and mapping permafrost environments. The often vast archive of historic aerial photographs and their potential for detailed visual interpretation are the main advantages of this method.

Airborne hyperspectral sensors with tens to hundreds of narrow bands in the VIS, NIR, and SWIR spectra enable detailed spectral descriptions of, for example, lithology, vegetation and lake water, but have not yet been applied to permafrost hazards. The method requires advanced geometric and radiometric pre-processing of data.

Airborne laser profiling and laser scanning (i.e. airborne LIDAR) are powerful tools for acquiring high-resolution and high-precision DTMs. Using repeat DTMs, it is possible to derive vertical terrain changes and in some cases, horizontal displacements. Most instruments record more than one return per laser pulse, and some record the complete return waveform. Some laser scanning instruments also record the signal intensity. Airborne laser scanning has a particularly strong potential for assisting detailed hazard assessments.

Airborne SAR has rarely been used for permafrost studies. The microwave spectrum, however, has considerable potential because of its ability to image in all weather conditions and at night, and to extract surface and subsurface characteristics that influence the backscatter from the ground such as roughness and moisture. The main application of airborne SAR is the generation of DTMs in areas of frequent cloud cover where laser scanning and aerial photogrammetry are of limited utility.

Airborne passive microwave sensors and airborne thermal infrared sensors are occasionally used in permafrost research for investigating surface temperature.

Airborne remote sensing offers advantages such as high spatial resolution and customer control over the acquisition time. However, methods may be costly and difficult to apply, for example, in conflict zones or very remote regions. Satellite sensors on the other hand provide coverage of large areas without the need for ground access, data are comparably cheap and accessible, and a repeat cycle of a few days is possible for some sensors.

Ground-Based Remote Sensing Techniques

Ground-based remote sensing techniques are suitable for studies of small areas, high-frequency monitoring and early warning systems. The following methods can be used for investigating permafrost-related threats (see Table 3):

- terrestrial photogrammetry
- touch-less laser range finders and terrestrial laser scanning
- terrestrial real and synthetic aperture radar
- automatic cameras, webcams, or video cameras

Combinations of Data and Methods

Analyses of data obtained using different sensors have become increasingly common. This development is driven by the greater number of sensors and data that are available and by the ongoing need to provide rapid, timely and reliable information, in particular for disaster management.

Of particular promise for hazard assessment and disaster management is the multi-temporal fusion of optical and SAR data to take advantage of different sections of the electromagnetic spectrum (Singhroy *et al.*, 1998; Ostir *et al.*, 2003; Coulibaly and Gwyn, 2005; Delacourt *et al.*, 2007). SAR data, for example, can bridge gaps due to cloud cover in data from optical sensors or complement the spectral content of optical data. For example, snow moisture conditions that are barely detectable using optical sensors alone can be inferred using SAR (Rott, 1994; König *et al.*, 2001). An overview of data combination strategies is given in Kääb (2005b).

Table 2 Overview of airborne re	smote sensing methods used, or pote	ntially suitable for permafrost problem and	d hazard studies.
Airborne method	Techniques	Parameters, remarks	Selected references
Hard copy or digital aero-photogrammetry	Hard-copy images, digitised images, diorial imagery	Surface characteristics	Kääb and Vollmer (2000); Kääb and Haeberli (2001); Kaufmann and Ladstädter (2002)
	Mono and stereo techniques Panchromatic, colour, near-infrared,	Digital elevation models	2003); Kääb (2002, 2005b); Kershaw (2003); Strozzi <i>et al.</i> (2004); Ødegård <i>et al.</i> (2004); Frauenfelder <i>et al.</i> (2005); Lantuit
	multispectral Matching of repeat images	Terrain displacements	and Pollard (2005); Roer <i>et al.</i> (2005); Couture and Riopel (2006); Jorgenson <i>et al.</i> (2006); Otto <i>et al.</i> (2007)
Airborne hvnersnectral imaøinø	Spectrometry	Spectral signatures	Crowley et al. (2003); Dozier and Painter (2004): Harris et al. (2006)
Airborne LIDAR/laser scanning	Laser profiling/scanning Single- or multiple-return pulses; full waveform Matching of repeat DTMs	Digital elevation models; terrain displacements; surface roughness; vegetation structure	Kennett and Eiken (1997); Baltsavias et al. (2001); Stockdon et al. (2002); Geist et al. (2003); Lutz et al. (2003); Janeras et al. (2004); Glenn et al.
Airborne SAR	Single-pass; along-track, cross-track, interferometry	Digital elevation models; backscatter; polarisation	(2006); van Asselen and Seijmonsbergen (2006) Koopmans and Forero (1993); Vachon <i>et al.</i> (1996); Floricioiu and Rott (2001); Nolan and Prokein
Airborne thermal sensing			(2003); Stebler et al. (2005) Whitworth et al. (2005); Applegarth
Airborne passive microwave sensing			Kim and England (1996); Vonder Mühll <i>et al.</i> (2001)
DTMs = Digital terrain models; {	SAR = synthetic aperture radar; LID.	AR = light detection and ranging.	

Table 3 Overview of ground-based	d remote sensing methods used, or p	otentially useful for permafrost problem a	and hazard studies.
Ground-based technique	Methods	Parameters, remarks	Selected references
Terrestrial photogrammetry	Interpretation; classification; stereo; matching of repeat images	Surface characteristics and changes; 3D object reconstruction; displacements	Lerjen <i>et al.</i> (2003); Kaufmann and Ladstädter (2004); Pitkänen and Kajutti (2004); Wangensteen
Touchless laser range finders, terrestrial laser scanners	3D point clouds	3D object reconstruction; displacements	Eat (2001) Bauer et al. (2003); Janeras et al. (2004); Rosser et al. (2005); Debetal at al. (2007)
Terrestrial real and synthetic	Interferometry	Digital elevation models;	Corsini et al. (2006); Luzi et al. (2006); Luzi et al. (2006); Luzi et al.
Automatic cameras, webcams, video	High-frequency repeat data acquisition	Surface changes; displacements; particle tracking	Christiansen (2001); Lerjen <i>et al.</i> (2007); Christiansen (2001); Lerjen <i>et al.</i> (2007); Harris <i>et al.</i> (2007)
3D = Three dimensional.			

SPECTRAL REMOTE SENSING OF SURFACE CONDITIONS

The technologically simplest form of image analysis, although by no means the least important and easiest, is the manual mapping of features of interest on the images. Where topography is rugged and the optical contrast weak, or for highly complex assessments, manual delineation of features may be superior to semiautomatic and automatic techniques. However, for rapid, repeated, or large area applications, automatic image classification is valuable. Available techniques range from classifications based on mono-spectral (i.e. greyscale), multispectral, hyperspectral, radar backscatter intensity or polarisation data, to spatio-spectral analyses utilising not only the spectral information of the image pixels but also their spatial context (object-oriented classification). A list of references is provided in Table 4.

In the microwave spectrum, analysis of the backscatter, the coherence of the SAR interferometric phase and the signal polarisation enable delineation and characterisation of terrain and its dynamics (Engeset and Weydahl, 1998; Floricioiu and Rott, 2001; Weydahl, 2001; Komarov *et al.*, 2002; Sjogren *et al.*, 2003; Yoshikawa and Hinzman, 2003).

Permafrost, which is strictly speaking a thermal phenomenon, cannot yet be directly remotely sensed. However, indicators, processes or boundary conditions of permafrost and permafrost-related threats can be detected remotely including for example thaw lakes, ice-wedge polygons, rock glaciers, active-layer detachments, thaw slumps, vegetation types and snow cover distribution (Table 4). Similarly, objects and processes that can be connected to permafrost-related threats can be investigated through spectral remote sensing analysis including for example glacier lakes (Huggel *et al.*, 2002; Wessels *et al.*, 2002; Kääb *et al.*, 2003), steep glaciers (Salzmann *et al.*, 2004; Fischer *et al.*, 2003; Mars and Houseknecht, 2007).

Remote sensing of climate variables, climate indicators and their changes is important, given potential future impacts of climate change on the cryosphere. Remote sensing techniques for monitoring surface temperatures, atmospheric conditions, snow cover, vegetation and sea ice (Peddle and Franklin, 1993; Duguay *et al.*, 2005) can thus provide early evidence of developing permafrost hazards and hazard zones (Nelson *et al.*, 2002). Similarly, other changes in boundary conditions, which might lead to permafrost threats, can be investigated through spectral-domain remote sensing, for example forest fires or burnt forest as potential triggers of detachment failures and/or thaw slumps (Lewkowicz and Harris, 2005a).

Processes	Remote sensing	Selected case studies and remote sensing applications
 Permafrost-related floods 1) Breaching of moraine lake dams Ground ice content in moraine dams plays an important role in the stability of moraine dams through its influence on hydraulic permeability, angle of repose and resistance to erosion (e.g. during a lake outburst or piping) 	Monitoring of elevation changes due to thaw settlement Monitoring of displacements due to deforming ground ice	Watanabe <i>et al.</i> (1995); Clague and Evans (2000); Haeberli <i>et al.</i> (2001); Huggel <i>et al.</i> (2002); Quincey <i>et al.</i> (2005); McKillop and Clague (2007)
 Failure or overtopping of temporary dams Permafrost-related sources of temporary dams: active-layer detachments, thaw slumps, landslides, periglacial debris flows, periglacial rock avalanches, rock glacier advance and instabilities 	Detection of damming and dammed lakes depending on spatial resolution, temporal resolution and timing of remote sensing system; time-series particularly useful Monitoring of thickness changes and kinematics of long-lasting dams	Ufimtsev <i>et al.</i> (1998); Huggel <i>et al.</i> (2002); Kääb <i>et al.</i> (2003); Strom and Korup (2006)
 Growth and breaching of thermokarst lakes Progressive lake growth through thermal convection. Growth may destroy installations at the lake shore. Outburst causes similar to (1) and progressive melt of ice/permafrost dam 	Spectral detection of related lakes; time-series particularly useful	Kääb and Haeberli (2001); Wessels <i>et al.</i> (2002); Frohn <i>et al.</i> (2005); Hinkel <i>et al.</i> (2005, 2007); Smith <i>et al.</i> (2005); Grippa <i>et al.</i> (2007); Mars and Houseknecht (2007); Quincey <i>et al.</i> (2007)
 4) Displacement waves in lakes Displacement waves impact on people, natural and artificial lake dams, and installations. Waves may trigger lake outbursts of types (1) and (2). Permafrost-related causes of waves: lake impacts of rock avalanches, landslides, debris flows 	Assessment requires integrative remote sensing and modelling approaches of source processes	No direct airborne and spaceborne remote sensing application. Cf. Tinti <i>et al.</i> (1999); Walder <i>et al.</i> (2003)
5) Enhanced runoff from permafrost Permafrost is typically impermeable to surface water, resulting in runoff concentration at the permafrost table. Temporary water storage in or underneath permafrost is particularly difficult to investigate but suggested for rare cases (causes: taliks; ice-melt in permafrost; temporary water blockage in or under the permafrost). The enhanced runoff is a potential trigger of debris flows	Not directly investigated by remote sensing	No published remote sensing applications. Cf. Haeberli <i>et al.</i> (1990); Zimmermann and Haeberli (1992)

Table 4 Permafrost-related problems and threats and their assessment by remote sensing.

(Continues)

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Table 4 (Continued)

Pro	cesses	Remote sensing	Selected case studies and remote sensing applications
Per 6)	<i>mafrost-related floods (continued)</i> Adverse effects of permafrost creep Permafrost creep (e.g. rock glaciers) can inundate land and destabilise or destroy constructions situated on or in it	Monitoring of permafrost deformation by repeat high-resolution optical remote sensing, SAR interferometry and laser scanning	Hoelzle <i>et al.</i> (1998); Burger <i>et al.</i> (1999); Kaufmann and Ladstädter (2003); Kenyi and Kaufmann (2003); Strozzi <i>et al.</i> (2004); Kääb (2005b); Roer <i>et al.</i> (2005); Wangensteen <i>et al.</i> (2006); Kääb <i>et al.</i> (2007)
Per 7)	<i>mafrost-related mass movements</i> Periglacial debris flows Thaw changes mechanical and hydrological properties of frozen ground and temporally increases its water content. As a consequence the susceptibility to periglacial debris flows may increase. Temporary runoff concentration (5) and ground saturation by water is, thereby, involved as trigger	Only detectable using remote sensing when accompanied by changes in surface geometry. Cf. (1)	Haeberli <i>et al.</i> (1990); Haeberli (1992a, 1992b); Zimmermann and Haeberli (1992); Hoelzle <i>et al.</i> (1998); Chiarle <i>et al.</i> (2007); Kneisel <i>et al.</i> (2007)
8)	Rockfall from rock glacier front Continuous transport of surface debris over the rock glacier front may lead to local rockfall threatening people and mountain infrastructure	Remote sensing see (6)	Bauer <i>et al.</i> (2003); Kääb and Reichmuth (2005)
9)	Destabilisation of frozen debris slopes In rare cases entire sections of rock glaciers or frozen debris slopes may destabilise. Can lead to (6), (7) and (8).	Slow movements detectable using high-resolution remote sensing. Methods of (6) and monitoring of crevasse formation	Dramis <i>et al.</i> (1995); Kaufmann and Ladstädter (2002); Roer <i>et al.</i> (2005); Kääb <i>et al.</i> (2007)
10)	Rockfall and rock avalanches from frozen rock faces The thermal regime and ground ice in frozen rock faces have complex thermal, mechanical, hydraulic and hydrological effects on rock stability and can cause mass movements. Processes are also related to (insulating) snow and surface ice and their changes	Detection of changes in snow and surface ice cover by optical sensors; monitoring of increasing rockfall activity from repeat optical data (e.g. automatic cameras, or laser scanning); deformation of rock flank from laser scanning and ground-based SAR	Wegmann <i>et al.</i> (1998); Haeberli <i>et al.</i> (2005); Rosser <i>et al.</i> (2005); Fischer <i>et al.</i> (2006); Noetzli <i>et al.</i> (2006); Rabatel <i>et al.</i> (2007)
11)	Active-layer detachment Changes in the thermal, hydrological and mechanical ground conditions can lead to detachment of the active layer. May lead to (2), (3), (4), (12)	Detection from (repeat) high-resolution optical and microwave data; elevation changes and volumes from repeat DTMs (optical, SAR, laser scanning)	Duguay and Lewkowicz (1995); Lewkowicz and Duguay (1999); Lewkowicz and Harris (2005a, 2005b) See also (12) and (13)

(Continues)

Processes	Remote sensing	Selected case studies and remote sensing applications
 Permafrost-related mass movements (continued) 12) Retrogressive thaw slumps Similar to (11) or a consequence of it. Progressive degradation of ground ice and erosion of ground 	See (11)	Duguay and Lewkowicz (1995); Lewkowicz and Duguay (1999); Burn (2000); Lantuit and Pollard (2005); Lyle and Hutchinson (2006); Wei <i>et al.</i> (2006) See also (11) and (13)
13) Permafrost-related landslides Similar to (11) and (12) or a consequence of it	See (11); movements from matching of repeat images, SAR interferometry; loss of interferometric-phase coherence	Foriero <i>et al.</i> (1998); Kääb (2002, 2005b); Zhen <i>et al.</i> (2003); Couture and Riopel (2006); Lyle and Hutchinson (2006); Alasset <i>et al.</i> (2007); Delacourt <i>et al.</i> (2007); Singhroy <i>et al.</i> (2007) See also (6), (11) and (12)
Other permafrost-related threats 14) Thaw settlement, subsidence and frost heave Changes in permafrost surface elevation due to changes in ground ice content from ice-lens accumulation or thermokarst processes; often connected to an increase or decrease of active-layer thickness; affects construction and infrastructure; may lead to (1), (3), (5), (7), (9)–(13). Thaw and frost heave processes may be natural or anthropogenic in origin (e.g. changes in snow-cover regime under structures, basement heating, forest fires)	Monitoring of vertical changes from repeat high-precision DTMs (laser scanning) or DInSAR Detection of trigger processes (e.g. vegetation changes due to forest fire, storm, and pests)	Rignot and Way (1994); French <i>et al.</i> (1996); Swanson (1996); Kääb <i>et al.</i> (1997); Moorman and Vachon (1998); Wang and Li (1999); Zhijun and Shusun (1999); Nelson <i>et al.</i> (2001); Komarov <i>et al.</i> (2002); Sjogren <i>et al.</i> (2003)
15) Erosion of river banks and sea coasts Combined thermal and mechanical erosion; may lead to (11)–(14)	Spectral detection from repeat high-resolution optical and microwave data; detection from differences between repeat DTMs (airborne and terrestrial photogrammetry, airborne SAR, airborne and terrestrial laser scanning)	Stockdon <i>et al.</i> (2002); Brown <i>et al.</i> (2003); Johnson <i>et al.</i> (2003); Rosser <i>et al.</i> (2005); Mars and Houseknecht (2007); Wangensteen <i>et al.</i> (2007)

Table 4 (<i>Continue</i>	d)
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DTMs = Digital terrain models; SAR = synthetic aperture radar; DInSAR = differential interferometric synthetic aperture radar.

Many permafrost-related threats involve terrain changes over time, requiring multi-temporal methodologies for their assessment. Related strategies include (Schowengerdt, 1997; Kääb, 2005b):

• *multi-temporal data overlay and comparison*, where the results from mono-temporal image classifications are compared or superimposed (Kääb and Haeberli, 2001; Yoshikawa and Hinzman, 2003; Smith *et al.*, 2005) (Figure 1);

- *animation*, where repeat images or derived classifications are shown sequentially;
- *multi-temporal false colour composites* (FCCs), where the individual channels of a colour image (in most cases red, green, blue) stem from different acquisition times (Figure 2). FCCs can



Figure 1 Outlines of a thermokarst lake in selected years for 1967–94. Note the asymmetrical lake growth towards the massive ground ice in the south. The displacement of the northern lake shore is a consequence of lake-level lowering. The lake had to be drained because of an impending outburst. The topography of the lake bottom and the surrounding surface, represented by 2.5 m contour lines, was photogrammetrically determined after lake drainage in late 1995 (Haeberli *et al.*, 2001; Kääb and Haeberli, 2001).

be composed from optical or microwave images (Ostir *et al.*, 2003; Kääb, 2005b);

• *image algebra*, also called band math, or algebraic expressions, where a change image is computed from two or more multi-temporal images through algebraic band operations such as spectral band ratios (R)

$$R_{i12} = \frac{DN_{i1}}{DN_{i2}}$$

or normalised differences (normalised difference index, NDI)

$$NDI_{i12} = \frac{DN_{i1} - DN_{i2}}{DN_{i1} + DN_{i2}}$$

where DN_{i1} and DN_{i2} are the digital numbers at times 1 and 2, respectively, of an image pixel in spectral band *i* at the same geolocation (Huggel *et al.*, 2002; Kääb, 2005a, 2005b).

• *multi-temporal principal component transformation* (PCT), where the first principal component computed from a multi-temporal image data set indicates the largest radiometric changes between the images (Schowengerdt, 1997). Multi-temporal PCT is useful for sets of numerous repeat data where FCCs or simple image algebra fail, such as in the case of frequent data acquired by lowor medium-resolution optical or microwave sensors like MODIS, Advanced Very High Resolution Radiometer (AVHRR), MERIS, SSM/I, or the long Landsat time-series.

• *multi-temporal classifications*, where repeat data sets are included in a supervised or unsupervised classification scheme, and the change classes and non-change classes (e.g. class 'forest-to-thaw lake') are derived automatically or through training the classification algorithm using changed terrain elements.

These techniques can be used with both optical and SAR data. Accurate geographic co-registration of the repeat data is obviously mandatory for any change detection procedure.

GENERATION OF DTMS

DTMs represent a key data set in most investigations of permafrost hazards. Furthermore, DTMs are needed



Figure 2 Deposits of the 20 September 2002 rock/ice avalanche at Karmadon, North Ossetian Caucasus. Change detection was undertaken using a multi-temporal red-green-blue (RGB) composite. Red: ASTER band 3 of 22 July 2001 (upper right image); green and blue: ASTER band 3 of 13 October 2002 (lower right image). Avalanche track and deposits, as well as lakes dammed by these deposits become visible in the false colour composite (left). The dashed outline marks the avalanche path running from south to north, the deposits in front of a gorge at the upper edge of the image, and the lakes, which were dammed by the avalanche deposits (Kääb *et al.*, 2003; Haeberli *et al.*, 2005; Huggel *et al.*, 2005). Red-coloured changes on north-facing slopes are due to different shadow/illumination conditions between the acquisition dates.

in several remote sensing data processing steps such as illumination correction and orthorectification.

Satellite Stereo

An efficient method of generating DTMs for virtually every terrestrial location on Earth is satellite alongtrack stereo from sensors such as ALOS PRISM, ASTER, SPOT-5, Ikonos and Quickbird. Along-track stereo sensors have one or more cameras with an oblique viewing angle in the direction of the sensors orbit azimuth in addition to the common nadir-looking camera (Figure 3). For polar and mountain environments, where surface conditions can change rapidly, along-track stereo acquired within minutes during one overflight is preferable to cross-track. Cross-track stereo instruments rotate the stereo camera perpendicular to the flight direction towards an area that was imaged from a neighbouring track, in some cases weeks or months earlier. The SPOT satellite is the satellite system most frequently used for cross-track stereo. Satellite stereo DTMs are produced using digital photogrammetric methods with a vertical accuracy approximating the pixel size of the applied sensor (e.g. 15 m for ASTER; Figure 3) and with typical horizontal grid spacings equivalent to 2–4 pixels (Kääb, 2002, 2005a; Toutin, 2002; Berthier *et al.*, 2004; Cuartero *et al.*, 2005).

Large errors in DTMs derived from optical satellite stereo can occur due to steep mountain flanks facing away from the oblique stereo sensor (Figure 4). Northern slopes, for instance, are strongly distorted or



Figure 3 Geometry of two satellite along-track stereo systems for digital terrain model generation. Left: ASTER's nadir channel (3N) and backward-looking channel (3B) form a stereo scene with 15 m spatial resolution. Right: The ALOS PRISM sensor has a forward channel in addition to nadir and backward channels. All three form a triplet scene with nominal 2.5 m resolution (see also Figure 4).

even hidden in the backward-looking stereo channel of the descending ASTER. This problem is largely overcome by the ALOS PRISM instrument that has forward, nadir and backward-looking channels (the so-called triplet mode; Figure 3). Large DTM errors also occur for particularly rough topography with sharp peaks, that are too small to be definitively matched between the stereo partners. Insufficient optical (radiometric) contrast, for example on snow, and similar features such as trees may lead to erroneous matching of stereo parallaxes and corresponding DTM errors. DTM errors are often accompanied by low correlation values from the stereoparallax matching procedure and can thus be identified using the matching correlation channel of the DTM.

Another simple and efficient method for evaluating DTMs and detecting errors is to produce multiple orthoimages using the same DTM, but with source images from different positions, such as the stereo pairs from along-track stereo. Vertical DTM errors translate into horizontal distortions, which change with different incidence angles and can thus be easily



DTM from PRISM N and B

DTM from PRISM F, N and B

SRTM DTM

Figure 4 Digital terrain models (DTMs) of mountainous terrain in the Tien Shan, produced from the ALOS PRISM nadir and backward-looking channels (left) and the PRISM forward, nadir and backward channels (middle). For comparison, a section of the Shuttle Radar Topography Mission DTM is shown in the right panel. DTM errors on north slopes (white arrow), which face away from the backward channel, are much reduced by adding a forward channel to the system. Generation of the PRISM DTMs was done together with C. Narama.

visualised by animated overlay or other change detection techniques (Kääb, 2005a, 2005b).

DTMs made from satellite stereo show characteristics that are different from the characteristics of DTMs derived using SAR interferometry. Merging DTMs from satellite stereo with DTMs from satellite InSAR combines the advantages of both sensor types. An essential processing step before merging or comparing multi-source DTMs is accurate coregistration of the data sets.

Radar Interferometry: SRTM

Sensors in the microwave spectrum are able to overcome the limitations of weather and sunlight dependency of optical sensors. InSAR can be used to generate DTMs (Renouard *et al.*, 1995; Crosetto, 2002). DTMs from spaceborne repeat-pass interferometry such as provided by Envisat, ERS 1/2 and RADARSAT have a vertical accuracy of metres and a spatial resolution of tens of metres. Improved accuracy is expected from the new high-resolution SAR sensors ALOS PALSAR, TerraSAR-X and RADARSAT 2.

A particularly interesting data set originated from the single-pass SRTM conducted in February 2000, which produced DTMs with about 30 m (1 arc-second, SRTM1) and 90 m (3 arc-seconds, SRTM3) grid size, and with a vertical accuracy ranging from a few metres to decametres (Figure 4; Kääb, 2005a; Berthier *et al.*, 2006). The SRTM covered the continents between 60° N and 54° S so it cannot be used for high-latitude permafrost hazard management. Due to radar shadow, foreshortening, layover and insufficient interferometric coherence, the SRTM DTM has significant voids in some areas such as high mountains. In such cases, fusion of spaceborne photogrammetric DTMs and the SRTM DTM can be a promising approach.

The spatial resolution of airborne SAR DTMs is metres or less, and their vertical accuracy for mountainous terrain is decimetres to metres, depending on the wavelength used. Current systems (Aero-Sensing airborne SAR (AeS-1), Geographic SAR (GeoSAR), Topographic SAR (TOPSAR)) use X- to P-band SAR (3 cm to 80 cm wavelength) (Vachon *et al.*, 1996; Nolan and Prokein, 2003; Stebler *et al.*, 2005). Most airborne InSAR sensors apply single-pass interferometry. However, multiple overflights with different azimuths may be required to overcome limitations from radar shadow or layover effects.

Aerial Photogrammetry

Aerial photogrammetry applies techniques similar to the spaceborne optical methods, although with higher accuracy due to the better spatial image resolution generally available. Digital photogrammetry based on digitised hard-copy images or digital imagery enables automatic DTM and orthoimage generation (Hauber *et al.*, 2000; Kääb and Vollmer, 2000). Depending on the image scale and pixel size, DTMs have a vertical accuracy of centimetres to metres and a spatial resolution of metres to decametres (Kääb and Vollmer, 2000).

Aerial photogrammetry is a particularly important tool in view of the existing large archives of analogue airphotos, which for many areas are the earliest and longest remotely sensed time-series and thus are invaluable for quantifying temporal change. Most aerial photographs are produced from negative film. However, digital frame or linear array cameras are increasingly being used (Hauber *et al.*, 2000; Otto *et al.*, 2007). The possibility of generating DTMs and orthophotos from digital imaging in near real-time offers an important advantage in disaster management and response.

Airborne LIDAR

DTM accuracy that is similar or better than that provided by airborne photogrammetry can be obtained from airborne laser scanning (or, LIDAR) (Baltsavias et al., 2001; Stockdon et al., 2002; Geist et al., 2003; Janeras et al., 2004; Glenn et al., 2006; van Asselen and Seijmonsbergen, 2006). LIDAR provides good results over snow, where photogrammetric methods have problems due to the lack of radiometric contrast. LIDAR DTMs have a spatial resolution of metres and the added details of the terrain can permit more sophisticated and accurate geomorphic interpretation and analysis of terrain dynamics. Recording multiple return-pulse maxima or even full returnpulse waveform enables, for example, allows analysis of surface roughness and discrimination between terrain elevation and vegetation top elevation. Airborne laser scanners are increasingly able to record the signal intensity (Lutz et al., 2003) and are equipped with electro-optical imaging devices that enable combined analyses of image and elevation data.

TERRAIN ELEVATION CHANGE AND DISPLACEMENT

Two types of terrain displacement can be measured using remote sensing methods: (1) displacement of surface particles and (2) elevation change at a specific location (Figure 5). Particle displacements are typically three-dimensional, but can be vertical only,



Figure 5 Gruben rock glacier, Swiss Alps. Overlay of the horizontal surface velocities (vectors) and the colour-coded changes in elevation, both for 1970 to 1995, derived from aerial photographs (Kääb *et al.*, 1997). To the northeast, a patchy distribution of horizontal velocities and high rates of thaw settlement indicate dead-ice occurrences that are not in thermal equilibrium. To the southwest, a coherent flow field and almost constant thickness point to creeping permafrost in thermal equilibrium. The measurements were done in relation to hazard assessment associated with the larger thermokarst lake (see Figure 1).

for example for thaw settlement. Elevation changes are point measurements independent of the displacement of surface particles.

Terrain Elevation Change

Terrain elevation change over time can be determined from vertical differences between repeat DTMs. The changes are indicators of processes such as thaw settlement and subsidence, frost heave and mass movements, thus their detection can be an important step in permafrost hazard assessment and disaster mapping (Figures 5 and 6; Kääb *et al.*, 2005a; Lantuit and Pollard, 2005; Delacourt *et al.*, 2007). The accuracy of the calculated vertical changes is a function of the accuracy of the repeat DTMs that are used (Etzelmüller, 2000; Kääb, 2005b). Pre- and post-processing procedures help to improve this accuracy:

Pre-processing (i.e. procedures done before DTM subtraction).

Accurate co-registration of multiple DTMs is necessary to obtain elevation changes free of systematic errors. If the repeat DTMs are produced using the same method (e.g. optical stereo), the co-registration can be assured by orienting the original data (such as repeat satellite or aerial imagery) as one combined, multi-temporal data set with shared ground control points and all the images connected by multi-temporal tie points (Kääb and Vollmer, 2000; Kääb, 2005b).

If the original sensor model and orientation are unavailable, or if the DTMs have different sources, matching can significantly reduce systematic errors in vertical DTM differences. Through correlation techniques, the vertical and horizontal shifts of the 'slave DTM' can be measured with respect to the 'master-DTM' so that the vertical differences between



Figure 6 Elevation changes between 1970 and 1994 on a moraine dam in the Gruben area, Swiss Alps. The dam is situated at the lower boundary of discontinuous permafrost. Related ground ice bodies are believed to play a role in the stability of the dam (Haeberli *et al.*, 2001). The large breach in the middle of the figure stems from lake outbursts in 1968 and 1970. The measured elevation changes reveal dead-ice degradation of -20 to -30 cm a⁻¹ vertically to the south of the lake. Aerial photograph courtesy of swisstopo.

the DTMs being co-registered are minimal for the stable terrain sections. An optimal horizontal and vertical shift, rotation, scale, or higher order transformation between the DTMs can be computed and the 'slave DTM' transformed accordingly (Pilgrim, 1996; Li *et al.*, 2001; Kääb, 2005b). DTM correlation focuses on stable terrain with sufficient relief (i.e. topographic contrast). Products derived from the DTMs, such as orthoimages (Berthier *et al.*, 2004), profiles, slope or curvature maps, can also be matched.

Post-processing of elevation differences.

Once the raw differences between repeat DTMs are computed, it is necessary to filter them because the noise in the differences is larger than in the original DTMs (Kääb, 2005b). The task is to define a noise model suited to the process under investigation. Filters can be used for the spatial domain (e.g. median, medium, Gauss) or for the spectral domain (e.g. Fourier or wavelet) (Kääb *et al.*, 1997; Kääb, 2005b).

A well-established method for detecting terrain elevation changes is subtraction of repeat aerophotogrammetric DTMs. A large number of applications exists, including measuring volumes of deposited materials (Clague and Evans, 2000), ground ice aggradation or degradation (Kääb *et al.*, 1997), thermokarst development and slope instability (Kääb and Vollmer, 2000; Kääb, 2005b; Lantuit and Pollard, 2005). Repeat laser scanning will increasingly be used in such studies (Geist *et al.*, 2003; Chen *et al.*, 2006).

Elevation changes from repeat satellite stereo can only be measured for a limited number of processes due to the relatively low accuracy of such DTMs. Nevertheless, the accuracy is sufficient to detect and quantify large changes in terrain, such as from avalanches, large landslides and thaw slumps (Berthier *et al.*, 2004; Kääb, 2005b; Lantuit and Pollard, 2005).

DInSAR can be used to detect vertical terrain changes. However, strictly speaking this technique tracks three-dimensional terrain surface shifts rather than elevation changes at fixed positions, and is therefore described below.

Lateral Terrain Displacement

Lateral terrain movements can be a primary hazard (e.g. landslides) or may set in motion other processes that develop into hazards (e.g. river damming by a thaw slump). The measurement of terrain displacement, that is the movement of surface particles, from repeat image data can thus support hazard assessment (Kääb *et al.*, 1997; Hoelzle *et al.*, 1998; Kääb, 2002; Casson *et al.*, 2003; Delacourt *et al.*, 2004).

If digital *image correlation techniques* are used, measurements are possible at the scale of the pixel size

of the sensor. Sub-pixel accuracy can be achieved but is limited by changes in terrain and illumination conditions between repeated data acquisition. Image matching techniques can be applied to terrestrial photos, aerial photos, optical satellite images, airborne and spaceborne SAR images, or high-resolution DTMs. Depending on the data and the technique employed, the horizontal, vertical or both components of surface displacement are measured (Kaufmann and Ladstädter, 2002; Berthier *et al.*, 2005; Kääb, 2005b).

The rate of terrain movement that can be detected, depends on the image pixel size, the temporal baseline and terrain preservation between the data acquisition dates. Slow rock mass displacements or permafrost creep with displacement rates of centimetres to metres per year can be detected and measured using aerial photographs and high-resolution satellite images (Ikonos, QuickBird, ALOS PRISM, SPOT-5) (Figures 5 and 7; Kääb, 2002; Delacourt *et al.*, 2004).

DInSAR enables measurements of terrain displacements of a few millimetres (Figure 8). Application of the method depends on interferometric coherence, topography and SAR imaging geometry; information is missing in layover and shadowed areas (Nagler et al., 2002; Eldhuset et al., 2003; Strozzi et al., 2004). Coherence is lost, for example, where the terrain is eroded or the surface wetness changes significantly (Weydahl, 2001; Sjogren et al., 2003). DInSAR provides only the line-of-sight displacement directly, that is the projection of the actual terrain displacement vector on the line between the terrain point and the sensor. In theory, the horizontal and vertical displacement components can be separated by combining line-of-sight displacements measured from ascending and descending orbits (Joughin et al., 1999). Application of this approach depends on the azimuth angle between ascending and descending orbits and the topography, which may limit terrain visibility from both orbits. Otherwise the vertical and horizontal components must be estimated or modelled from the type of terrain movement under investigation (Wang and Li, 1999; Strozzi et al., 2001). Typical DInSAR applications in permafrost hazard assessments are detection of rock mass movements, landslide movement and permafrost creep (Figure 8; Moorman and Vachon, 1998; Rott and Siegel, 1999; Nagler et al., 2002; Strozzi et al., 2004; Tait et al., 2005; Singhroy et al., 2007).

DInSAR can be applied to dominant and permanent microwave backscatterers such as buildings or distinct rock formations using a large number of SAR scenes, reducing atmospheric error effects and enabling detection of small movements due to landslides or settlement processes (Dehls *et al.*, 2002; Colesanti *et al.*, 2003; Hilley *et al.*, 2004).

SAR interferometry techniques rely on phase coherence between repeat data. Loss of interferometric phase-coherence, however, does not necessary mean that the method has failed. It may rather point to processes such as destruction of vegetation on a landslide, or ground ice melt (Moorman and Vachon, 1998; Weydahl, 2001; Sjogren *et al.*, 2003).

DInSAR and optical image matching methods for permafrost hazard assessments are highly complementary; as a very general rule, DInSAR may work where image matching fails, and vice versa.

REMOTE SENSING APPLICATIONS AND LIMITATIONS

A combination of the above-listed methods is often used to remotely sense permafrost-related hazards, problems and disasters. A detailed list of hazard and problem types, remote sensing possibilities and references to case studies are given in Table 4. Here, the capabilities and limitations of remote sensing for these applications are discussed.

Permafrost-related Floods

In cold mountain regions, ground thermal conditions in moraines are often important to the stability of *moraine-dammed lakes*. For example, permafrost or near-permafrost conditions cause the long-term preservation of dead-ice bodies, which leave behind cavities when they melt (Richardson and Reynolds, 2000). Repeat DTMs can reveal thaw settlement resulting from melt of ground ice (Figure 6). Due to the large spatial variability and the small magnitude of such vertical changes, remote sensing methods of high spatial resolution and high vertical accuracy are required, typically aerial and terrestrial photogrammetry and airborne and terrestrial laser scanning.

Matching of repeat high-resolution images or LIDAR-derived DTMs may also enable detection of lateral displacements on moraine dams due to ground ice deformation or melt. In theory, SAR interferometry can also be used, but in practice the deformation features are usually too small compared to the spatial sensor resolution to allow reliable identification. New high-resolution SAR sensors such as TerraSAR-X and others under development may improve the situation.

A number of remote sensing methods support susceptibility assessments relating to moraine-dammed lakes. These include identification of moraine dams, measurement of their geometry for stability and volume assessments, monitoring of lake areas and



Figure 7 Instability of a rock glacier snout (Turtmanntal, Swiss Alps). Upper panel: velocity vectors measured from airphotos of 1987 and 1993; lower panels: orthophotos of the terminus section of the rock glacier. Images of 1975, 1987 and 1993 are courtesy of swisstopo; the 2001 image is a linear array charge-coupled device (pushbroom) image taken by the High Resolution Stereo Camera Airborne (HRSC-A) camera, courtesy of Department of Geography, University of Bonn. The rock glacier instability led to enhanced rockfall and required construction of a protection dam (not shown). Data processing by I. Roer (Roer *et al.*, 2005; Kääb *et al.*, 2007).

generation of DTMs for modelling potential permafrost occurrences.

Deposits from *permafrost-related slope failures* can *dam rivers*, causing outbursts and floods when these dams fail. High temporal and spatial sensor resolution and automatic systematic analyses based on repeat satellite data would be necessary to initially detect such river damming on an operational level. Such remote sensing systems are not yet fully operational but are expected in the near future (see the section on disaster management below). SAR data have a particularly large potential for such tasks because microwave sensors are independent of sunlight and weather. In the case of a dam that lasts long enough to allow acquisition of repeat data, techniques similar to the ones for moraine dams can be applied to monitor its development and that of the associated lake (Figure 2).

The progressive growth of *thermokarst or thaw lakes* may lead to their breaching and subsequent flooding of downstream areas. These lakes are typically easily detectable and grow slowly so that their distribution and development can be reliably monitored using operational airborne and spaceborne



Figure 8 Upper panel: Synthetic aperture radar (SAR) interferogram of the Gruben area, Swiss Alps, using ERS data (Strozzi *et al.*, 2004). The displacements of three rock glaciers (white arrows) are easily detectable. Rectangle (a) marks the area shown in Figure 5. Rectangle (b) marks the area shown in the lower panel. Lower panel: aerial photograph of a rock glacier tongue. The rock glacier creep transports debris onto a steep slope and thus causes rockfall and debris flows. SAR processing by T. Strozzi. Aerial photograph courtesy of swisstopo.

optical and SAR sensors (Figures 1 and 5). It is rarely possible, however, to predict the time of breach and the breach process mechanism using remote sensing.

There are cases reported where *runoff concentration at the permafrost table* has triggered debris flows and other mass movements. Such sub-surface

processes are not generally suitable for direct investigation by remote sensing.

Permafrost-related Mass Movements

Permafrost creep, exemplified by the creep of rock glaciers, may have adverse effects such as inundation of land, destabilisation of constructions and rockfall from the rock glacier front (Table 4). Permafrost creep can transport debris into locations from which debris flows or landslides originate. Feature matching based on repeat terrestrial, airborne and high-resolution spaceborne data, matching of repeat LIDAR-derived DTMs and SAR interferometry has proven very useful for detecting and quantifying lateral displacements on creeping permafrost (Figures 5,7 and 8). The global availability of repeat spaceborne SAR data and repeat spaceborne optical data with a spatial resolution of 1 m or better enables velocity measurements to be performed for a large number of problematic rock glaciers. In order to be detectable from repeat optical data at a statistically significant level, the total lateral displacement should be larger than the spatial resolution of the sensor used. Changes in excess ice content and local instabilities on rock glaciers can be measured from differencing high-accuracy DTMs generated from aerial stereo-photogrammetry or terrestrial and airborne laser scanning (Figure 5).

The steep topography of rock walls severely limits the applicability of most remote sensing methods for monitoring frozen rock walls and related rockfall and rock-avalanche threats. Often, parts or entire rock faces are hidden in images due to adjacent topography, or are highly distorted due to the steep surface slope. The most promising remote sensing techniques for monitoring rock faces include: aerial photogrammetry and automatic terrestrial imaging for monitoring changes such as ice and snow cover, as well as rock avalanches; terrestrial and airborne laser-scanning for deriving repeat high-resolution DTMs and geometry changes; ground-based radar interferometry for deformation measurement. Spaceborne sensors are less useful for examining steep rock faces with the exception of images taken with large off-nadir angles pointing towards the rock face under study (e.g. using the backward or forward channels of a stereo sensor). Space imagery is useful for inventorying rock avalanche events and for assessing related parameters such as distance, overall slope and possibly volume.

Active-layer detachments, thaw slumps and permafrost-related landslides are often detectable by disturbed vegetation in repeat optical images, providing the surface area affected is much larger than the spatial sensor resolution. DTMs from repeat terrestrial or aerial photogrammetry and terrestrial or airborne LIDAR have proven highly suitable for quantifying elevation changes and advected volumes of mass movements. Where surface features are preserved during the movement process, surface velocities may be measured using repeat terrestrial and airborne images or detailed DTMs (Figure 7). In areas with little vegetation, the deformation of permafrost-related landslides with intact surfaces can potentially be measured using SAR interferometry. If the surface is disturbed, the landslide area may become traceable as a zone of distinct loss of interferometric-phase coherence. Installation of artificial SAR targets (corner reflectors) may enable monitoring of the movement, although only at individual points. On landslides that cover a large area and cause thickness changes of many metres to tens of metres, highresolution spaceborne optical stereo data can also be used for assessing elevation changes and horizontal displacements, and in rare cases, even spaceborne LIDAR.

Remote sensing is able to assist modelling of terrain susceptibility to permafrost-related mass movements, for example by providing DTMs, geomorphometric parameters, surface characteristics and their changes with time.

Other Permafrost-related Threats and Problems

Surface elevation changes due to *thaw settlement*, *subsidence and frost heave* can only be detected with high-precision DTMs such as ones derived using terrestrial and airborne photogrammetry or laser scanning (Figure 5). Several studies suggest that it is also possible to detect vertical changes of this type over large areas using differential SAR interferometry. A number of remote sensing sensors and methods (e.g. repeat optical or SAR spaceborne data) are well suited for detecting and monitoring surface changes, which eventually can trigger thaw settlement and ground instability (e.g. snow-cover variations and changes in vegetation due to forest fires, storms or pests).

Erosion of frozen river banks, lake shores and sea coasts can be detected from almost any repeat optical or microwave data due to the good spectral contrast between land and water providing the lateral change on the ground is significantly greater than the spatial resolution of the sensor (Figure 1). Automatic change detection procedures can be particularly useful for monitoring large areas. Differencing of repeat high-resolution DTMs enables quantification of eroded volumes. Airborne laser scanning is increasingly being used for such studies.

EARLY WARNING AND DISASTER RESPONSE

Remote sensing in relation to permafrost can be applied at all stages of the risk cycle: before, during, or after the occurrence of a problem or disaster (Figure 9). Directly after an event, for example, remotely sensed images can support the delimitation of affected areas and undamaged access routes for emergency personnel, as well as detection of damage severity in order to prioritise targets for searchand-rescue operations. Rapid understanding of the full nature and extent of an event is crucial for many emergency and relief actions, for example in order to assess possible subsequent hazardous events that could threaten civil protection personnel. The main applications of remote sensing in the rehabilitation and reconstruction phases of the risk cycle are detailed damage assessment maps, to be used for repair, insurance purposes and reconstruction planning.

Most research-related remote sensing applications to permafrost-related hazards are found within assessments of susceptibility, hazard and risk (see Table 4). Applications to other stages of the risk cycle are often performed at the operational and applied level, for example by civil protection authorities and engineering companies. Land-use planning, and planning and construction of prevention or protection structures are often supported by remotely sensed data such as detailed DTMs and orthoimages. Remote sensing also helps improve preparedness, for example in planning evacuation and access routes.

Airborne and spaceborne remote sensing in general are not suitable for direct forecasting of disasters and monitoring of events due to relatively low temporal resolution. However, ground-based remote sensing methods can be very useful for early warning purposes after a hazardous site has been identified, perhaps using airborne and spaceborne remote sensing. Laser and radar range finders or automatic cameras can track natural or artificial targets on unstable terrain and trigger warnings when certain thresholds are exceeded.

Autonomous on-board decision systems on satellites could automatically select imaging targets as well as times and sensor settings, and thereby increase the efficiency of on-board systems, and reduce the reaction time and effort for hazard and disaster management (Davies *et al.*, 2006a; Ip *et al.*, 2006).

Integrating remote sensing for the management of permafrost-related problems serves three major applied and scientific needs: it provides (a) overviews of problems and damage extent, (b) frequent monitoring and (c) disaster documentation (Figure 9). The



Figure 9 The risk cycle and application fields of remote sensing for management of permafrost-related hazards and disasters.

first and second requirements are directed towards search-and-rescue operations and civil protection, and primarily require rapid and repeated data acquisition. The short repeat cycle for some satellite sensors makes spaceborne methods suitable for disaster management (Kääb *et al.*, 2003). Due to the limitations of optical remote sensing during periods of cloud cover and darkness, the application of repeat weatherindependent and sun-independent SAR data can be especially important (Kerle and Oppenheimer, 2002).

A number of initiatives are presently underway to create satellite constellations designed for disaster management, for example, DMC (Tobias *et al.*, 2000; Kerle and Oppenheimer, 2002; Curiel *et al.*, 2005; Davies *et al.*, 2006b). Most of the planned and operational constellations rely on groups of small or micro-satellites, some with combined optical and SAR sensors, to address the crucial requirements of disaster management from space: short-reaction time, the potential for high revisit frequencies, and day-and-night and all-weather capability.

Remotely sensed documentation of a disaster, even if the data are not analysed immediately, can be an important source of information for thoroughly investigating the event and the processes involved at a later date. This can allow scientific and applied conclusions of broader interest to be drawn (Huggel *et al.*, 2005).

The International Charter 'Space and Major Disasters' offers potentially important remote sensing support for managing large permafrost-related disasters. Under this contract, space agencies and commercial satellite companies provide, under certain circumstances, rapid and free emergency imaging. Sensors include Envisat, ERS, IRS, RADARSAT, Landsat, SPOT, ALOS and DMC. Selected national and international civil protection, rescue and security authorities can activate the charter (www.disasterscharter.org). The ASTER sensor on the Terra spacecraft can also be activated for supporting disaster management (Kääb *et al.*, 2003).

The Global Earth Observation System of Systems aims at a global infrastructure that generates comprehensive, near-real-time environmental data, information and analyses, based on existing and new remote sensing sensors and systems. An important target application of this network system is disaster management.

CONCLUSIONS AND PROSPECTS

Current developments in air and space technologies suggest that there remains considerable potential for these technologies to assist hazard experts and responsible authorities in managing the challenges they face in cold environments. Remote sensing, therefore, is becoming an increasingly important and integrative component of permafrost hazard assessment and management.

Airborne and spaceborne remote sensing offers support for assessing the hazard susceptibility, rather than trigger conditions and short-term forecasting of events. An exception to this general rule may be high-frequency spaceborne emergency imaging when used for monitoring meteorological events or observing changes in surface conditions that could trigger permafrost-related problems. Early warning of impending disasters is one of the ultimate goals of earth observation from space and air, and of the related technological development. To reach this goal, improvements will be needed in: the reaction time and temporal resolution of remote sensing systems, autonomous or computer-aided decisions about acquisition targets, the integration of high-resolution optical and SAR data, and data and information availability.

Assessment of permafrost hazards requires knowledge about the potential processes, their magnitude and their probability. Space- and airborne remote sensing can assist in detecting threats, but estimating event magnitude and frequency requires models and empirical data. A major application of remote sensing in permafrost hazard assessments is to provide data for numerical models in support of hazard assessments, such as DTMs and surface displacements for landslide modelling, or spectral surface characteristics for energy-balance modelling.

The spatial resolution and accuracy of most spaceborne methods make them applicable for regionalscale permafrost hazard assessments at the level of hazard indication maps (scales 1:25 000–1:50 000). For more detailed hazard assessments, airborne methods, high-resolution spaceborne methods, or terrestrial surveys are necessary.

Modern space technologies enable virtually everyone to access space imagery and use visualisation tools, independent of political and geographical restrictions. This fundamental 'democratisation' process in relation to many types of natural threats presents new opportunities, dangers and responsibilities for the public, governments and the experts involved. On the one hand, remote sensing is an invaluable tool for the detection and management of permafrost hazards, problems and disasters. On the other, it is increasingly possible to generate conclusions based on easily accessible space and aerial images without the necessary expert knowledge. Such information may develop into false warnings and significantly complicate the work of governments and planners.

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