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Living with landslide risk in Europe: Assessment, effects of global change, and risk management strategies

7th Framework Programme
Cooperation Theme 6 Environment (including climate change)
Sub-Activity 6.1.3 Natural Hazards

Deliverable D4.4

Guidelines for the selection of appropriate remote sensing technologies for monitoring different types of landslides

Work Package 4.2 – Remote Sensing technologies for landslide detection, monitoring and rapid mapping

Deliverable Leader: ITC Revision 2: – Ready for Approval

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SUMMARY

New earth observation satellites, innovative airborne platforms, high precision laser scans, and enhanced geophysical surveys are just a few examples for the increasing diversity of remote sensing technologies used in the study of landslides. The application of advanced sensors and analysis methods can help to significantly increase the quantity and quality of our understanding of potentially hazardous areas and helps to reduce associated risk. However, the choice of the optimal technology, analysis method and observation strategy requires careful considerations of the landslide process in the local and regional context, and the technological advantages and limitations of each technique. To guide and facilitate the decision process for stakeholders this deliverable provides an overview of available state-of-the-art remote sensing techniques and their applicability for different landslide types, scales and risk management steps.

The document was elaborated as a deliverable for the SafeLand project (EC-FP7), which targets the development and application of innovative tools for risk assessment and management for landslides. The deliverable was compiled by the Faculty of Geo-Information Science and Earth Observation-ITC at the University of Twente with contributions from landslide and remote sensing researchers from 12 European institutions.

The compiled guidelines provide detailed fact sheets for 30 different remote sensing techniques with details on their accuracy, data availability, costs, technological limitations, etc., and the applicability of each technique for different landslide types, observational scales, displacement rates, and risk management phases is evaluated. The document provides a good basis for a comparison of available techniques and the list of evaluated criteria may serve as a comprehensive checklist to support informed decisions.

Citation:

Note about contributors

The following organisations contributed to the work described in this deliverable:

Lead partner responsible for the deliverable:
Faculty for Geo-information Science and Earth Observation – ITC
University of Twente, United Nations University

Deliverable prepared by:
André Stumpf, Norman Kerle, Jean-Philippe Malet

Partner responsible for quality control:

Norwegian Geotechnical Institute (NGI)

Regula Frauenfelder

Contributors:

i. Analisi e Monitoraggio del Rischio Ambientale (AMRA Scarl)
G. Fornaro

ii. Bureau de Recherches Géologiques et Minières (BRGM)
D. Raucoules

iii. Centre National de la Recherche Scientifique (CNRS):
J.P. Malet

iv. Faculty for Geo-information Sciences and Earth Observation (ITC):
A. Stumpf, N. Kerle

v. Geological Survey of Austria (GSA):
I. Baron, R. Supper

vi. Geological Survey of Norway (NGU):
T. Oppikofer, J-S. L'Heureux

vii. Geological Survey of Slovenia (GeoZS):
M. Carman

viii. Joint Research Centre (JRC):

M. van den Eeckhaut, J. Hervás

ix. Università degli studi di Firenze (Unifi):
V. Tofani, S. Segoni, N. Casagli, F. Cantani, E. Intrieri

x. Università degli studi di Salerno (UNISA):
D. Peduto, L. Cascini

xi. Universitat Politècnica de Catalunya (UPC):
J. Gili, J. Moya

xii. Université de Lausanne (UNIL):
A. Abellán, M.-H. Derron, M. Jaboyedoff, C. Michoud

CONTENTS

List of acronyms

DLR-ZKI	Center for Satellite Based Crisis Information of the German Aerospace Center
DSM	Digital Surface Model
DTM	Digital Terrain Model
GB-InSAR	Ground-Based Interferometric SAR
GMES	Global Monitoring for Environment and Security
JRC	Joint Research Center
LiDAR	Light Detection and Ranging
LOS	Line of Sight
SAFER	Services and applications for emergency response Emergency Response Service
SAR	Synthetic Aperture Radar
SERTIT	Service Régional de Traitement d'Image et de Télédétection
SERVIR	Sistema Regional de Visualización y Monitoreo
UAV	Unmanned Aerial Vehicles
UNOSAT	United Nations Institute for Training and Research - Operational Satellite Applications Programme
VHR	Very-High Resolution

1. Introduction

This document provides condensed guidelines for the selection of the most suitable remote sensing technologies according to different landslide types, displacement velocities, observational scales and risk management strategies. The main part of the document gives an overview of the capabilities of different techniques to detect, characterize, map and monitor landslides and can be used to initially constrain the choice of methods to a few techniques that seem most feasible for the landslide process at hand. Before final decisions on the methods to be used are taken, further information and expertise will typically be required. Therefore, links to relevant SafeLand project deliverables are provided throughout the text. For further information Annex 1 provides an overview of recent scientific studies that applied the mentioned techniques. Links to relevant database and software tools can be found in Annex 2. This Annex also provides a list of expert institutions that could be consulted for recommendations on observational strategies.

Users of this document should consider that it provides a snapshot of the currently available knowledge and technology. In the near-future, the launch of new satellites, better data access (e.g. Global Monitoring for Environment and Security - GMES), lower data prices and on-going enhancement of processing algorithms, will lead to the maturing of many currently new or experimental techniques into methods suitable for operational use (see also SafeLand deliverable D4.5); at the same time, other traditional methods may become obsolete.

In this document we focus mainly on technological and geomorphological aspects. Social aspects (such as preparedness, awareness) are only briefly touched (Chapter 2.5) and we refer to deliverables D5.5-D5.7 where these important aspects are discussed in more detail.

State-of the art remote-sensing technologies, data types and basic processing steps and important case studies have been reviewed in the SafeLand deliverable D4.1. The most recent outcomes of remote sensing studies of SafeLand partners for the creation and updating of inventory maps are presented in D4.3, which also contains a thorough review on the role of remote sensing in the collection of input data for the creation of hazard and risk maps. An in-depth evaluation of future technologies and methods tested within the framework of the project is provided in deliverable D4.5.

This document provides a synoptic overview of proposed remote sensing techniques and their applicability for the monitoring of different types of landslides for stakeholders. The selection of the optimal technology needs to consider not only aspects of the landslide process itself, such as volumes, displacement rates or type of movement, but also the integration of observation strategies into current risk management strategies. The final outcome of this **deliverable is presented as a set of inter-related tables** that can be used by stakeholders to obtain an overview of methods and technologies suitable for their particular needs.

Monitoring can be generally defined as the systematic repetition of observations of a particular object or area (Figure 1). Landslide monitoring in particular comprises a number of different tasks that will influence the choice of the optimal technique and we distinguish between detection, fast characterization, rapid mapping and long-term monitoring. Those monitoring tasks are defined as follows:

- **Detection**: new landslides recognition from space- or airborne imagery
- **Rapid mapping**: fast semi-automatic image processing for change detection and/or target detection; hotspot mapping
- **Fast characterization:** retrieving information on failure mechanism, volume involved, and run-out length
- **Long-term monitoring**: processing data for retrieving deformation patterns and time series

Figure 1: Definition of monitoring as the systematic repetition of observations

Considering the great diversity of techniques and possible environmental situations it might in some cases become necessary to deviate slightly from these terms. In addition, it is worth noting that generally a repetition of detection, characterization and rapid mapping might be considered as long-term monitoring in most cases.

Chapter 2 contains technical details of 30 different remote sensing techniques and information about their applicability with respect to different landslide types, displacement rates, observational scales and risk management phases. As a starting point the technical details of each technique are summarized in **fact sheets.**
Obviously some of the available remote sensing techniques have been particularly designed for observations in the submarine domain (fact sheets D2-3). Regardless the slides' domain (terrestrial, submarine) the choice of the best technique will of course depend on the landslide type, whereas also several other factors cannot be neglected.

Available resources and other more site specific factors certainly play an important role but are difficult to generalize and need careful consideration in the regional and local context. The focus of this document is therefore to assess the set of optimal techniques considering general factors including the landslide type, expected displacement rates, observational scales and risk management phases. Although, in practice those factors are interrelated and should not only be considered in isolation the systematic evaluation of remote sensing techniques requires examining them one by one. As a consequence chapter 2 contains four further subsections in which the applicability of each technique is evaluated according to different displacement rates (2.2), types of movement 2.3), observational scales (2.4) and risk management phases (2.5), respectively. The evaluation was carried out by the involved project partners according to a set of harmonized **tables** and is presented in such way (Tables 1-5). An **explanatory text** accompanies each table to ease the access for the reader, state a synthesis of the table content, and provides additional information for the stakeholders (e.g. examples of best practice, recommendations for a few most commonly encountered cases).

For further reading and as a guide to specialists two annexes are provided, where Annex 1 includes recent references for case studies that illustrate the described methods, and Annex 2 lists a number of databases, software tools and relevant authorities for the satellite, airborne and ground-based remote sensing. It should be noted that it is not intended to provide complete lists but rather a good starting point for the search for further information.

1.1. Fact sheets for different remote sensing techniques

The fact sheets provide an overview of available datasets, related analysis methods and resulting datasets evaluating the following characteristics.

- **Sensor type**
- **Platform**
- **Recording system**
- **System name**
- **Contribution institutions**
- **Applicable methods (technical reference in D4.1 and D4.3)**
- **Method Nr.**
- **Data product**
- **Accuracy level**
- **Availability of alternatives to gather the same type of information**
- **Spatial coverage**
- **Spatial resolution**
- **Temporal resolution**
- **Costs of input data**

- **Additional costs for rapid response**
- **Additional costs for processing**
- **Development status**
- **Advantages**
- **Limitations**

The document contains fact sheets for 30 different techniques. Each method is referenced with a **Method-Nr.** which is subsequently used to indicate its applicability and usefulness in the tables for landslide velocities, landslide types, observational scales, and risk management phases. The **Method-Nr.** is composed by a **letter** which indicates the underlying remote sensing technology **and a number** that provides unique identification within each group. The letters stand for the following principle groups.

A = passive optical
B = active optical
C = microwave
D = airborne geophysics, offshore surveys

To keep the number of factsheets manageable not all possible platforms (especially for aerial imagery) are indicated, and only ground-based, aerial and satellite remote sensing are distinguished. It should be considered that similar as for satellite remote sensing (a comprehensive database is hosted at http://gdsc.nlr.nl/FlexCatalog/catalog.html#), a multitude of airborne platforms is available and especially UAVs Unmanned Aerial Vehicles () have recently been gaining greater importance. For the sake of completeness an overview of common airborne platforms is provided in Figure 2.

Beside the accuracy of the output data and advantages/limitations of each technique the costs and elaboration time for the different products are evaluated quantitatively or, where this is not possible, a qualitative rating is given. The great number of different possible scenarios makes it difficult to give a detailed **cost** estimate for each situation. Nevertheless some estimates are provided in order to enable at least a relative comparison of competing methods. Several of the assessed techniques (e.g. multi-temporal and stereo views of optical systems and Synthetic Aperture Radar (SAR) require observation at multiple dates (or viewing angles) leading to additional data costs. Costs for stereo recordings are included in the costs per spatial unit and additional costs for multitemporal scenes can be expressed as costs per temporal and spatial unit. It is further distinguished between costs for operationally acquired datasets and additional costs (e.g. satellite programming), as the latter is of particular interest for rapid response to disastrous events. At the end of each factsheet restrictions and advantages of each method are shown and we refer the reader to the SafeLand deliverable D4.5 for a more thorough evaluation of recent technologies. The explanatory text for the factsheets (2.1.1) provides a comprehensive explanation of the significance of the listed items.

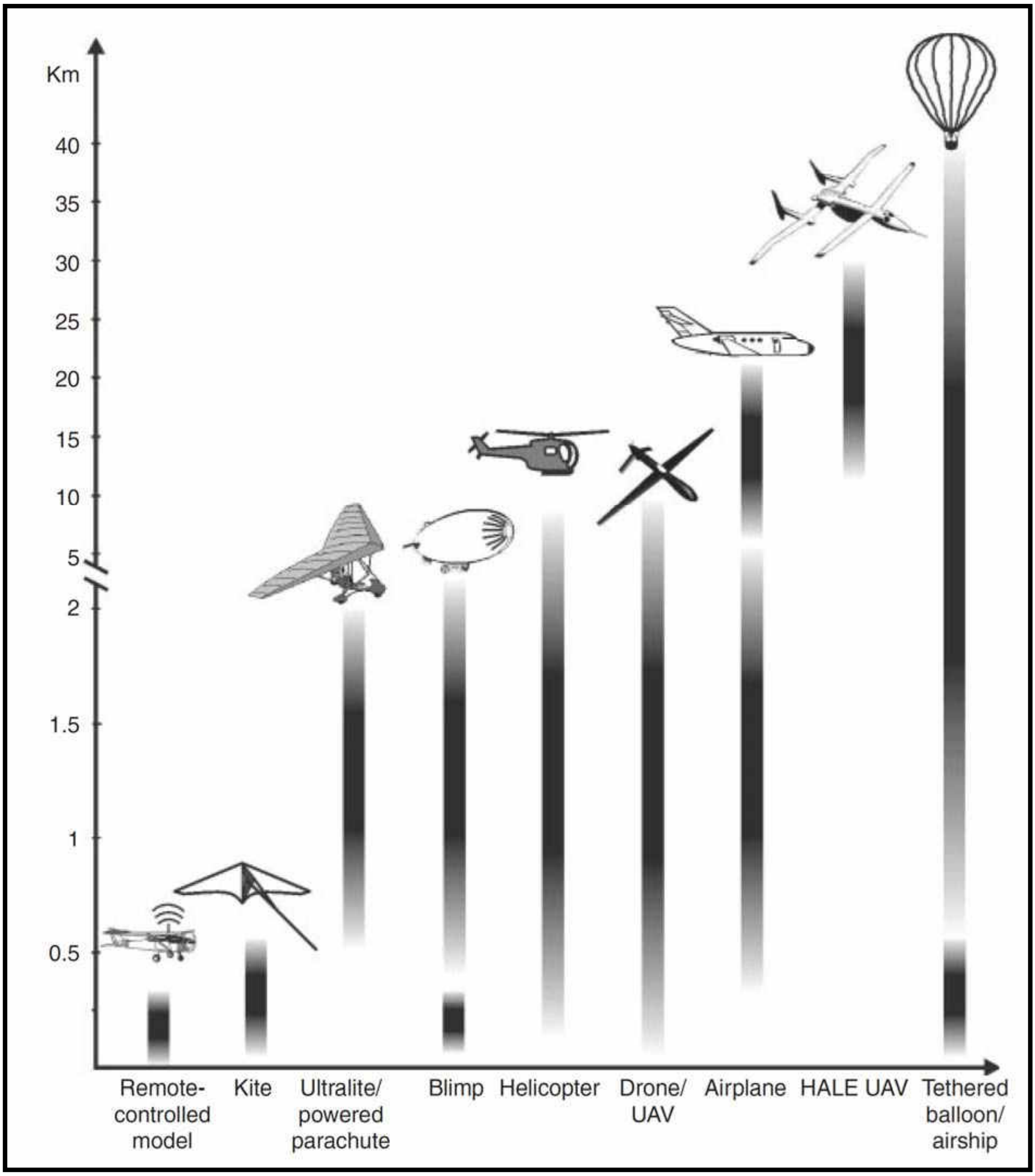


Figure 2: Overview of approximate minimum and maximum operating altitudes of different airborne platforms (shaded bars) [*Kerle et al.*, 2008].

1.2. Applicability according to different displacement rates, landslide types, observations scales and within phases of the risk management cycle

1.2.1. TABLES 1 & 2: APPLICABILITY TO DIFFERENT DISPLACEMENT RATES

The displacement rate of a landslide is a critical factor for the application of many remote sensing techniques. Some methods may not be sensible enough to reliably measure very slow displacement, whereas many methods do not provide sufficiently high repetition rates of the measurements to monitor rather fast moving masses. In such cases the choice of the right method will depend on the expected velocities, which have been previously measured with other techniques or which are anticipated from historic knowledge about a particular place or area. The velocities of landslides can easily exceed the capacities of most measuring devices and the time needed for coordinated human reactions. Indeed most landslides fall into this latter group and can typically only be investigated with remote sensing techniques in a post-failure stage.

The **Method-Nr.** from the factsheets are arranged in the table, evaluating the performance of proposed methods for the main tasks **detection**, **fast characterization, rapid mapping** and l**ong-term monitoring** and typical ranges of displacement rates. The table content is explained in detail in section 2.2.1.

1.2.2. TABLE 3: APPLICABILITY TO DIFFERENT LANDSLIDE TYPES

The applicability of a particular technology also depends on the type of the process. A given landslide type entails for example a certain geometry of the displacement, which might be critical if the remote sensing technique is only sensitive to displacement and deformation in a certain direction. Flows for example typically comprise largely slope parallel displacement, whereas the vertical component of the displacement is comparatively small. Especially debris flows are often confined in narrow channels with a constrained the footprint in remote sensing images and restricted viewing geometries.

The **Method-Nr.** from the factsheets are arranged in the table, evaluating the performance of proposed methods for the main tasks **detection**, **fast characterization, rapid mapping** and l**ong-term monitoring** and **first order landslide types**. The table content is explained in detail in section 2.3.1.

1.2.3. TABLE 4: APPLICABILITY AT DIFFERENT OBSERVATION SCALES

A combination of the size of a particular landslide type, the area under investigation and local capacities will influence the targeted scale of most surveys. The described remote sensing methods provide data products with diverse spatial extent and resolution and consequently demonstrate different efficiencies on different scales. Most techniques based on satellite remote sensing yield measurement with regional coverage, whereas ground-based techniques typically provide greater details for local investigations.

The **Method-Nr.** from the factsheets are arranged here, evaluating the performance of proposed methods for the main tasks **detection**, **fast characterization, rapid mapping** and l**ong-term monitoring** on different spatial scales (**1:1000 - 1:250000**). The table content is explained in detail in section 2.4.1.

1.2.4. TABLE 5: APPLICABILITY WITHIN PHASES OF THE RISK MANAGEMENT CYCLE

Observation strategies should be elaborated in the spatial and historical context of the area under investigation. In section 2.5 a risk management cycle is adopted to highlight the importance of different tasks of remote sensing and suitable methods in different phases. Thereby we need to ask which methods are more suitable/ less suitable to deliver the necessary information required during the different phases. Especially during and immediately after major events this also requires to anticipate which information will be needed when, where and how fast and accurately it can be provided by the remote sensing technology.
As an input to the toolbox developed by WP2.3 (Development of procedures for QRA at regional scale and European scale) the table gives an overview of the applicability of proposed methods for landslide observations according to the main phases of the **risk management cycle**.

The **Method-Nr.** from the factsheets are arranged, evaluating the performance of each technique for the main tasks **detection**, **fast characterization, rapid mapping** and l**ong-term monitoring.** The table content is explained in detail in section 2.5.1.

2. Remote-sensing techniques for different landslide types

2.1. Available data and methods

The following sections accommodate factsheets for 30 different remote sensing techniques and explain how the technical details are presented.

2.1.1. Explanatory text

With reference to the factsheets, this section provides a general guideline on the technical details which need to be considered when selecting the right remote sensing technology for landslide monitoring.
Further details on which methods are actually suitable for different displacement rates, scales, landslide type and risk management tasks will be provided in the other sections and the **method-nrs.** noted in the fact sheets is used there to reference each technique.
Each factsheet provides an overview of several technical features concerning available remote sensing technologies. The factsheets should be used by end users as a support in selecting appropriate remote sensing technologies for their needs. In fact, an ultimate "universal" methodology does not exist; every technology has its own advantages and disadvantages. End-users should carefully consider them to select the methodology which represents the best compromise between pros and cons and which better meets their needs (and their budgets, after all).
The first row of the fact sheet contains basic information including the general **sensor type,** the **platform**, the **recording system** and common **system names**, the **applicable analysis methods** with links to deliverable D4.1., the **method-nr.** and typical **data products**.
Amongst all the technical features to take into consideration, **accuracy level** is one of the most important and it presents a wide range of values (from millimetres to tens of meters).
With respect to this feature, best outcomes can be obtained by means of ground based active optical sensors (such as distance-meters and total stations) and ground-based active microwave sensors (GB-InSAR). The first can provide 3D coordinates and 3D displacements with millimetric accuracy, the latter can provide, with the same accuracy level, interferograms, displacement maps, coherence maps and power images, using C- X- and Ku bands. In addition, SAR distance-meters can be used to assess the relative displacement along the line of sight (LOS) with sub-millimetre accuracy. A millimetric accuracy in measuring the displacement perpendicular to the LOS and in 3D can be obtained also by means of video supported tacheometers (ground-based passive optical sensors).

The poorest accuracy levels are encountered when using some airborne or satellite passive optical sensors. Only a metric accuracy is achieved, for example, when assessing horizontal displacement using airborne low cost non-metric cameras, airborne black and white metric cameras or 8-30 m ground sampling distance (GSD) satellites. Some satellite passive optical sensors (such as Landsat, Aster, Spot 1-4, Formosat, EO-1, DMC) have a medium resolution and they can be used to map only landslides larger than a few hundred squared meters.

The column "**alternatives**" takes into account another important feature that can guide the end user in the choice of the proper monitoring technique. In this column a qualitative statement is provided about the presence of alternative methods to derive the same information without the described technique. The range of options varies between the absence of alternatives and the presence of one or more substitutes which in addition present some advantages (e.g. they are cheaper) with respect to the described technique. As an example, GSD 8-30 m satellites are almost the only technique capable of measuring horizontal displacement fields over larger areas; low cost airborne non-metric cameras have few alternatives at similar costs; while in some cases high resolution – panchromatic satellites with GSD < 10 m could be conveniently replaced with multitemporal LiDAR and SAR measurements.

Another technical detail which end users should carefully consider during the selection of the most proper remote sensing technique for their needs is the "**coverage**". This feature provides a qualitative estimation of the area observable with each technique listed in the table. The coverage of each technique is expressed in terms of its range, or a typical value (in squared kilometres) of either the swath width or the area covered during a single campaign.
Spaceborne medium-resolution passive optical sensors (Landsat, Aster, Spot, Formosat, EO-1, DMC, etc.) are credited as the tools to achieve the largest coverage, which typically is in the range of thousands of km^2. These techniques are obviously preferable in regional scale studies, while for site specific applications, the capability to focus on a restrict spot may represent an additional value: all the ground-based technologies present the most limited coverage but they are commonly used in site-specific studies. For example, SAR distance-meters are used to assess the displacement in a single point, with a range up to 5 km.
When choosing the proper remote sensing technique, a trade-off between coverage and accuracy is needed, because in general a broader coverage corresponds to a poorer accuracy level, and vice-versa.

Another technical detail interconnected with coverage and accuracy level is the "**spatial resolution"**: the technologies applicable at the local scale have usually the higher spatial resolution: ground based passive optical sensors can have a centimetric spatial resolution (metric cameras and low cost non-metric cameras), and the most advanced LiDAR instrumentations can generate point clouds with a density up to 100 points/m^2. Conversely, spaceborne techniques usually provide a coarser spatial resolution (e.g., the original images of GSD 8-30 m satellites have a 15 m spatial resolution).

A good trade-off between coverage and spatial resolution can be obtained with metric multispectral airborne cameras, which have a typical resolution of 25-50 cm and a coverage that typically ranges from 10 to 500 square kilometres.

In the "**temporal resolution**" column of the factsheets, the range or typical revisiting time of each technique is listed. The range of values for this feature is very large, as the various techniques are employed in very different ways in the monitoring process. Actually, the temporal resolution of spaceborne sensors coincides with their revisiting time (i.e. the time elapsed between observations of the same point on earth). Cosmo Skymed at present grants the shortest revisit time (up to 4.5 hours), while other satellites have a temporal resolution in the order of days: the poorest temporal resolution (35 days) is obtained when using the InSAR L-band geared on ALOS PALSAR and JERS satellites and InSAR C-band geared on ERS-1/2, Radarsat, or ENVISAT SAR satellites. Passive optical sensors usually have the shortest temporal resolution, but a gap of several years can often occur between suitable images in the archive.
Airborne and some ground based technologies are usually employed on demand at specific time intervals; the surveys are typically repeated at yearly or monthly intervals, but in some recent applications these techniques have been employed with hourly or sub-hourly temporal resolution. If no new acquisitions are carried out, historical images are usually available at decadal intervals.
Concerning some ground based instrumentations (e.g. video cameras), the temporal resolution listed in the tables refer to the frame rate.

One of the features that may influence the end-users decision in selecting the technique to be used in the landslide monitoring are the **costs**. Obviously, other criteria being equal, the cheapest technology is commonly preferred.
For each technique three different costs are taken into account: the costs of the input data, additional costs for rapid response and additional costs for processing.
The "**costs for input data**" column provides the price of data per spatial unit (in Euro), together with a color-coded qualitative information (very high, high, medium, low and a very low price). In a few cases, input data can be acquired for free.
The cost for metric cameras can, for example, be nil as long as historical images are used. The opposite end of the range of the input data costs is occupied by airborne LiDAR: very high density point clouds (60 points/m^2) typically cost about 7k €/ m^2.

The **additional costs for rapid response** are minimal or inexistent for ground based passive optical sensors and for most part of the airborne ones. Depending on the locality ground based and airborne active optical sensors typically may require considerable additional investments to bring the sensor into place in emergency situations. For passive spaceborne data the additional costs are even greater, whereas during major disaster particular satellite images can be obtained for free by institutions enrolled in international initiatives such as the

'International Charter Space and Major Disasters', the 'Services and applications for emergency response Emergency Response Service' (SAFER), Sentinel Asia or 'Sistema Regional de Visualización y Monitoreo' (SERVIR)..
The **additional costs for processing**, software acquisition and instruments installation vary significantly even between different methods of the same technology. The processing costs for permanent scatterers, for example, range from 2,000 €/100 km^2 (retrospective analysis for up to 7 years over large areas) to 35,000 €/100 km^2 (retrospective analysis for up to 7 years over small areas). There exist also spaceborne technologies which have reduced processing costs: ASTER satellites data can be processed with free software. On average, ground-based passive optical sensors have the most reduced processing costs, since often just a camera calibration is needed.

The **development status** is another important feature that should be considered when choosing the proper monitoring technique, because it reflects the expertise level required for the application of the technology. The development status is taken into account in factsheet with a specific column, where a colour gradation (from red to green) highlights whether the development status is concept design, prototype, tested, commercially used or well established. The main advantage of using a well-established technique is that the unexpected problems should be limited or someway the solution should be known. In general, spaceborne techniques are less established than ground based or airborne techniques. Some passive optical sensors with high resolution multispectral or GSD<10 recording system are, for instance, still in a prototypal version, while ground based distance-meters and ground based total stations are well established technologies. Of course, technical improvements are accomplished in ground based technologies as well, and prototypes can be found also in this branch (e.g. high-resolution multispectral active optical sensors).

The last technical feature taken into account in the factsheets is the **estimated elaboration time**, which could have a relevant weight in the balancing of pros and cons of the various monitoring techniques. For some methods, the time gap between the acquisition of data and the moment in which they are fully employed is almost zero. This is, for example, the case for video-supported tacheometer, consumer-grade video cameras and low-cost non-metric cameras. It should be highlighted, however, that the latter require an installation and setup time that is usually about two months. Even ground based InSAR techniques require only a few minutes to perform the measurement while, among the satellites, Cosmo Skymed can provide an almost near-real time data distribution with monthly updates. Airborne geophysical sensors probably require the longest elaboration time: the whole process from data collection to complete data interpretation can take up to a few months.

In the last columns of each sheet, the main technical features of each technique are summarized and split in **advantages** and **limitations**.

The above mentioned set of criteria (summarized also on p. 9) was considered for each technique trying to provide exact quantities as far as possible. In cases where it was not feasible to provide single quantitative estimates a range of values is provided or a colour coding which gives at least a qualitative approximation. The following legend provides an explanation of the colour coding and we also refer to section 2.1.1 for further explanations.

Accuracy level				
very low (e.g. 1 00 m)	low (e.g. m)	medium (dm)	high(cm)	very high (mm)

- description of the accuracy achievable with the technique
- qualitative and/or in spatial units (e.g. m, m^2, m^3)

Alternatives				
almost none	few	a couple	several	many

- qualitative statement about the possibilities to derive extracted information with other remote sensing techniques or in-situ measurements

Coverage				
site specific	local	regional	continental	global

- quantitative / qualitative estimation of the data coverage for landslides in the European context

Costs of input data				
very high	high	medium	low	very low

- price of data per spatial unit in € or qualitative estimate
- considering single scene, multi-temporal acquisitions, costs of hardware and different acquisition modes

Additional costs for rapid response				
very high	high	medium	low	very low

- costs for satellite programming, rapid response teams, holding equipments available, etc.
- quantitative or qualitative

Additional costs for processing				
very high	high	medium	low	very low

- costs of operator, additional software and/or specialised hardware
- quantitative or qualitative

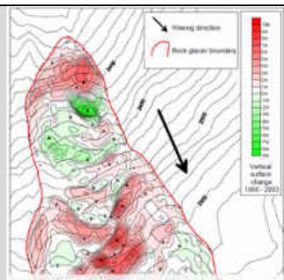
Development status				
concept design	tested prototype	multiple studies	commercial use	well established

- Maturity of the technology
- Expressing also the possibility to obtain access to the technology and the degree of expertise needed for operation

Estimated elaboration time				
more	month-years	days-month	hours-days	near real time-hours

- Semi- quantitative description including data acquisition and processing time

2.1.1. Fact sheets for different remote-sensing techniques

Surface reconstruction with close range photogrammetry	 modified after Ladstaedter and Kaufmann 2004	A1

Sensor type	Platform	Recording system	System names	Contributing institution	Applicable analysis methods	Method Nr.	Data product
Passive optical sensors	Ground – based, Low-altitude aerial	Metric cameras		ITC	Close range photogrammetric DSM generation (D4.1 Part A:2-3)	A1 (see also A7)	Historical volume budgets, vertical deformation, surface displacement

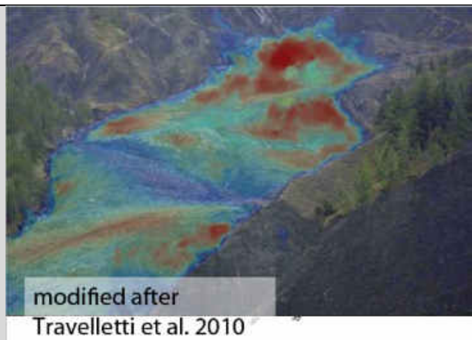
Accuracy level					Alternatives					Coverage					
		dm historic	cm with recent systems					Terrestrial LiDAR		Close range, up to 1km distance	Site specific				

Spatial resolution	Temporal resolution	Costs of input data				
10-50 cm	Historical images usually only recorded every few years					Nil as historical imagery is used

Additional costs for rapid response	Additional costs for processing					Development status				
Not assessed			Scanning		Camera calibration					

Estimated elaboration time					Advantages	Limitations
					• Exploitation of already historical imagery • One of the few sources for quantitative historic information on displacement and volumes • Relatively low costs	• Constrains on viewing geometry and gaps in occluded areas • Historic reconstruction only possible where regular surveys had been carried out • Increasingly difficult with low view angles • Inhomogeneous accuracies dependent on the image depth

Displacement measurements with terrestrial photographs



A2

Sensor type	Platform	Recording system	System names	Contributing institution	Applicable analysis methods	Method Nr.	Data product
Passive optical sensors	Ground - based	Low - cost non-metric cameras	e.g. Harbortonic Time-Lapse Package	CNRS	Digital Image Correlation of terrestrial photographs (D4.1 Part A: 2.4, 4.7)	A2 (see also A7)	Near-real time 3D surface displacement fields

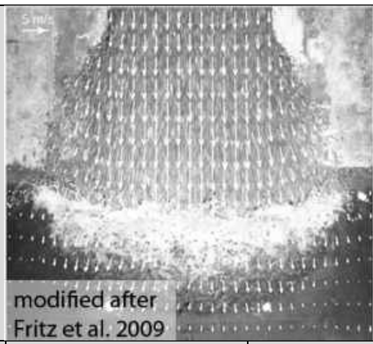
Accuracy level					Alternatives					Coverage					
			cm							Close range, up to 1km distance	Site specific	Local			

Spatial resolution	Temporal resolution	Costs of input data				
cm	Hourly and higher at daytime and suitable weather conditions				~ 2k EUR	Consumer grade camera, permanent terrestrial platform

Additional costs for rapid response	Additional costs for processing					Development status				
Not assessed					Camera calibration					

Estimated elaboration time					Advantages	Limitations
			Installation and setup ~2 month	Processing within min.	• Accurate monitoring of the displacement at low costs • Monitoring of the full field displacement	• Works only as long as the surface is visible (e.g. not with fog, snow or at night)

Displacement measurements with terrestrial videos



A3

Sensor type	Platform	Recording system	System names	Contributing institution	Applicable analysis methods	Method Nr.	Data product
Passive optical sensors	Ground - based	Video	Consumer grade video cameras	ITC	Image velocimetry, visual interpretation (D4.1, Part A: 2.5)	A3 (see also A7)	Failure history and velocity estimates

Accuracy level				
		dm		

Alternatives				

Coverage					
Close range, 10m - 1km distance	Site specific				

Spatial resolution	Temporal resolution
cm-m	typically 24 frames /s

Costs of input data					
				+ Power supplies, in total ~ 2k €	Consumer grade video camera

Additional costs for rapid response				

Additional costs for processing				
				Camera calibration

Development status				

Estimated elaboration time					Advantages	Limitations
			Installation and setup ~2 month	Processing within min.	• Potential for real-time monitoring of relatively fast moving landslides • Important information for process understanding	• Since direct visibility has to be guaranteed not very reliable for early warning • Currently more commonly used in laboratory experiments

Video-tacheometry

Source: Leica

A4

Sensor type	Platform	Recording system	System names	Contributing institution	Applicable analysis methods	Method Nr.	Data product
Passive optical sensors	Ground - based	Video supported tacheometer	e.g. Leica Viva TS15 Total Station	ITC	Image velocimetry (D4.1, Chapter 2, Part A: 2.5)	A4	Displacement perpendicular to the line of sight (3D displacement from additional tacheometer components)

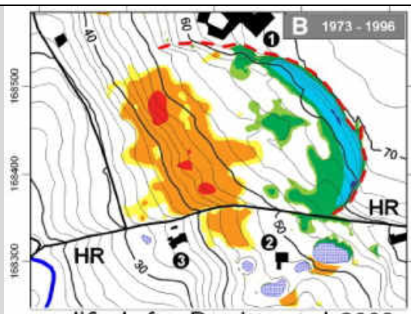
Accuracy level					Alternatives					Coverage					
				mm						Close range, 10m - 1km distance	Site specific	Local			

Spatial resolution	Temporal resolution	Costs of input data				
1-2m	typically 24 frames /s		> 40k € for video supported tacheometer			

Additional costs for rapid response					Additional costs for processing					Development status				
									Image processing software included					

Estimated elaboration time					Advantages	Limitations
			Some days for a fixed installation		• Measurement of displacement with millimetre accuracy • Suitable for fast and slow displacements	• Relatively high hardware price for small coverage • Maximum range < 500 m

Airborne stereo-photogrammetry



modified after Dewitte et al. 2008

A5

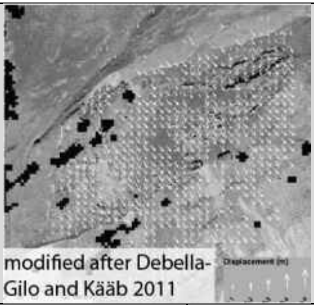
Sensor type	Platform	Recording system	System names	Contributing institution	Applicable analysis methods	Method Nr.	Data product
Passive optical sensors	Airborne	Metric cameras - black and white	ADS80, Ultracam, DMC	ITC	Stereophotogrammetric generation of multitemporal DTM and differencing (D4.1, Part A: 3.5.)	A5 (see also A7)	Vertical displacement, volume

Accuracy level					Alternatives					Coverage					
		1000 m^3 volume	dm for deformation		Few for historical displacements and volumes			Airborne LiDAR for present date		Typically 5-25 km^2	Site specific	Local			

Spatial resolution	Temporal resolution	Costs of input data				
0.2-5m, DTM depends on density of matching ground points , typically at least 4x image resolution	Decadal since 1930s, more frequently in the last decades			More recent 7-15 €/km^2		Low costs for historical imagery, <100 € per scene

Additional costs for rapid response					Additional costs for processing					Development status				
Not applicable						Scanning	Collection of ground control points	Co-registration						

Estimated elaboration time					Advantages	Limitations
	Manual point matching	Ground control points	Automated point matching	Scanning	• Low costs of historic imagery • Detailed reconstruction of vertical historical deformation and displaced volumes	• Temporal resolution highly depends on the availability of historic images • Deformation or failure volume most be relatively large

Displacement measurements with airborne photogrammetry	 modified after Debella-Gilo and Kääb 2011	**A6**

Sensor type	Platform	Recording system	System names	Contributing institution	Applicable analysis methods	Method Nr.	Data product
Passive optical sensors	Airborne	Metric cameras - black and white	ADS80, Ultracam, DMC	ITC	Digital Image Correlation of aerial photographs (D4.1, Part A: 3.5)	A6 (see also A7)	Horizontal displacement

Accuracy level				
	m			

Alternatives				
Few for historical displacements and volumes			Many for present day observations, e.g. space borne	

Coverage					
5-25 km^2	Site specific	Local			

Spatial resolution	Temporal resolution
Subpixel	Decadal since 1930s, more frequently in the last decades

Costs of input data				
		More recent 7-15 €/km^2		Low costs for historical imagery, <100 € per scene

Additional costs for rapid response				
Not applicable				

Additional costs for processing				
		Ground control points	Co-registration	Scanning

Development status				

Estimated elaboration time				
	Manual matching if no homologous points can be matched automatically	Automated point matching	Collection of ground control points	Scanning

Advantages	Limitations
• Low costs of historic imagery • Detailed reconstruction of horizontal displacement fields many synergies with method A5	• temporal resolution depends on frequency of surveys / typically displacement rates between 0.5 and 15m per year can be measured • movement must be coherent • decorrelation if surface aspect changes

Visual image interpretation

A7

Sensor type	Platform	Recording system	System names)	Contributing institution	Applicable analysis methods	Method Nr.	Data product
Passive optical sensors	Airborne	Metric cameras - multispectral		ITC	Visual interpretation (high resolution and at least colour information is desirable, D4.1, Part A: 2.2, 3.4, 4.2)	A7 (see also A1-14)	Landslide area, number of landslides, landslide types

Accuracy level					Alternatives					Coverage					
Dependent on the interpreter	m	Sometimes dm					VHR satellite imagery			5-25 km^2		Local	Regional		

Spatial resolution	Temporal resolution	Costs of input data				
25-50 cm	More frequently available since 1990s			More recent 5-10 €/km^2		Low costs for historical imagery, <100 € per scene

Additional costs for rapid response					Additional costs for processing					Development status				
Flight crew, airplane,…						Work hours of expert								

Estimated elaboration time					Advantages	Limitations
Month-years					• Established method for the creation of landslide inventories • No advanced image processing techniques needed for the analysis	• Subjective, time-consuming

Note: Visual interpretation of aerial photography is still the most commonly used technique to support the elaboration of landslide inventories and also commonly used to reconstruct the evolution of landslide over time. As indicated by references to **Method Nr.** obviously other image types can be considered. Present day VHR satellite imagery comprise significant spatial details and provide an alternative to airborne images that can be acquired more flexible and at considerably lower costs.

UAV-based aerial photography and photogrammetry		A8

Sensor type	Platform	Recording system	System names	Contributing institution	Applicable analysis methods	Method Nr.	Data product
Passive optical sensors	Airborne	Low cost non-metric cameras	Civil UAV remote sensing	CNRS	Photogrammetric analysis and visual interpretation	A8 (see also A7)	Surface features, horizontal displacement, deformation

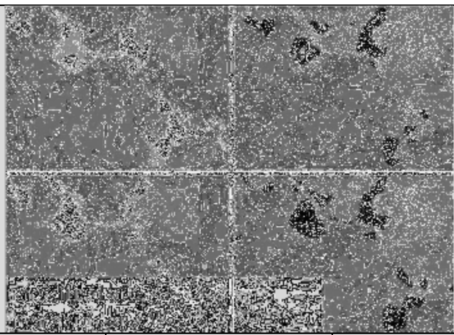
Accuracy level					Alternatives					Coverage					
	m displacement and DSM		cm, surface features		Little at low costs			Commercial systems		Typically 5 - 25 km^2	Site specific	Local			

Spatial resolution	Temporal resolution	Costs of input data				
5-10 cm	As needed (typically monthly-yearly)				40,000-60,000 € for platforms with geolocation systems (GPS/IMU)	Complete acquisition systems starting at 1000 €

Additional costs for rapid response					Additional costs for processing					Development status				
							Ground control points and co-registration of image from low-cost systems	5000-10000 € for photo-gram-metric software	Photogrammetric software					

Estimated elaboration time					Advantages	Limitations
	If manual point matching is employed	Ground control points and co-registration of image from low-cost systems	Visual interpretation		• Rapid and flexible deployment of sensor platforms • Very high resolution images • Low costs • Image registration without ground control points possible	• For low cost systems many ground control points are necessary • Limited coverage • Accuracy of multitemporal co-registration still rather low

Pixel-based classification of spaceborne images



A9

Sensor type	Platform	Recording system	System names	Contributing institution	Applicable analysis methods	Method Nr.	Data product
Passive optical sensors	Satellite	Medium resolution (GSD 8-30 m)	Landsat, Aster, Spot, Formosat, EO-1, DMC, etc.	ITC	Pixel-based classification and object-based refinement	A9 (see also A7)	Landslide area

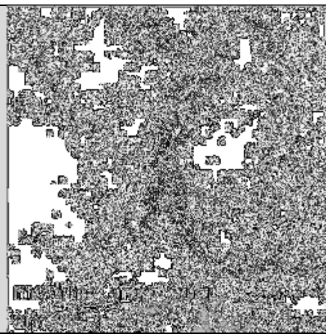
Accuracy level	Alternatives	Coverage
Land-slide larger than approx. 100 m^2	Visual interpretation is very time-consuming; Higher resolution sensors and more advanced image	Thousands of km^2

Spatial resolution	Temporal resolution	Costs of input data
> 8 m, landslide with a some 100 m^2 can be detected	~ 25 days from the same sensor, daily with different sensors	Approx. 5 €/ km^2 for daily image acquisition; SPOT imagery at 0.33 - 0.92 €/ km^2; Landsat ETM+ is available for free, ASTER at 0.03 €/ km^2, EO-1 at 0.06 €/ km^2, ALOS at 0.10 €/ km^2

Additional costs for rapid response	Additional costs for processing	Development status
Formosat-2, approx. 5 €/ km^2; SPOT 1,22 €/ km^2; Disaster Monitoring Constellation 0.144 €/ km^2; Free for members of the International Charter Space and Major Disasters	Professional software for object-based processing; Nil with open source software	

Estimated elaboration time	Advantages	Limitations
Trial and error threshold selection can be time-consuming	• Low cost of imagery • Applicable over large areas • Relatively easy to implement • Long-time series are available	• Relatively low accuracy (omission and omission errors are typically above 30%) • Individual landslides are not distinguished • Difficulties of post-classification comparison of multiple time-steps

Pixel-based change detection in spaceborne images



A 10

Sensor type	Platform	Recording system	System names	Contributing institution	Applicable analysis methods	Method Nr.	Data product
Passive optical sensors	Satellite	Medium resolution (GSD 8-30 m)	Landsat, Aster, Spot, Formosat, EO-1, DMC, etc.	ITC	Pixel-based change detection	A10 (see also A7)	Landslide area (event-based)

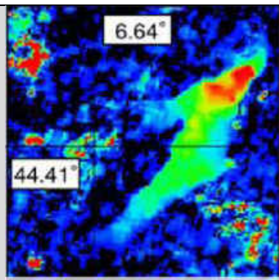
Accuracy level					Alternatives					Coverage					
		Can be high if all changes correspond to landslides			Visual interpretation is very time-consuming			VHR sensors and more advanced image analysis techniques		Thousands of km²					

Spatial resolution	Temporal resolution	Costs of input data				
> 8 m, landslide with a some 100 m² can be detected	Up to daily with satellite programming, often years between suitable images in the archive	Approx. 10 €/ km² for daily image acquisition			SPOT imagery at 0.66 - 1.84 €/ km²	Landsat ETM+ is available for free, ASTER at 0.06 €/ km², EO-1 at 0.12 €/ km², ALOS at 0.10 €/ km²

Additional costs for rapid response					Additional costs for processing				Development status					
	Formosat-2, approx. 5 €/ km²	SPOT 1,22 €/ km²	Disaster Monitoring Constellation 0.144 €/ km²	Free for members of the International Charter Space and Major Disasters				Radiometric normalization						

Estimated elaboration time						Advantages	Limitations
		Post-processing To separate different changes may be necessary	Trial and error threshold selection can be time-consuming			• Relatively inexpensive solution for mapping of affected terrain over wide areas • Event-based if time steps between images is short enough	• Threshold for changes must be selected • Suitable imagery is available with sparse temporal resolution or rather expensive when satellite programming is used • Other surface changes from vegetated to bare soil (e.g. deforestation, harvest) lead to commission errors

Displacement measurements with spaceborne photogrammetry



modified after Delacourt et al. 2007

A11

Sensor type	Platform	Recording system	System names)	Contributing institution	Applicable analysis methods	Method Nr.	Data product
Passive optical sensors	Satellite	Medium resolution (GSD 8-30 m)	Landsat, Aster, Spot, Formosat, EO-1, DMC, etc.	ITC	Digital Image Correlation (D4.1 Part A: 4.7)	A11 (see also A7)	Horizontal displacement

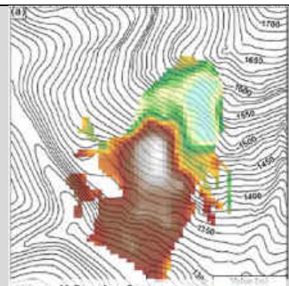
Accuracy level	Alternatives	Coverage
10 m	Unique for measuring horizontal displacement fields over larger areas	Swath width of 60 km and more

Spatial resolution	Temporal resolution	Costs of input data
> 8 m, vectors typically every 50-100 m	e.g. ASTER: every 16 days, since 2000	Approx. 5 €/ km² for daily image acquisition; Additional costs if other than free ASTER global DSM is used; SPOT imagery at 0.33 - 0.92 €/ km²; Landsat ETM+ is available for free, ASTER at 0.03 €/ km², EO-1 at 0.06 €/ km², ALOS at 0.10 €/ km²

Additional costs for rapid response	Additional costs for processing	Development status
Not applicable	Free-plugins for commercial software; Free software available	

Estimated elaboration time	Advantages	Limitations
Post-processing, filtering; Orthorectification, co-registration, subpixel correlation	• Large archives of inexpensive imagery • Can be performed without ground control points • Provides displacement fields	• Will not work if surface aspect changes strongly= decorrelation • As all optical techniques dependent on good visibility of the grounds • Quality is highly dependent on the used DTM

Spaceborne stereo-photogrammetry


modified after Martha et al. 2010

A12

Sensor type	Platform	Recording system	System names	Contributing institution	Applicable analysis methods	Method Nr.	Data product
Passive optical sensors	Satellite	High resolution - panchromatic (GSD<3 m)	SPOT, Cartosat-1, ALOS Prism	ITC	Stereophotogrammetric generation of multitemporal DSM and differencing of derived DTMs(D4.1 Part A: 4.3.)	A 12 (see also A 7)	Displaced volumes, extent, failure mechanism

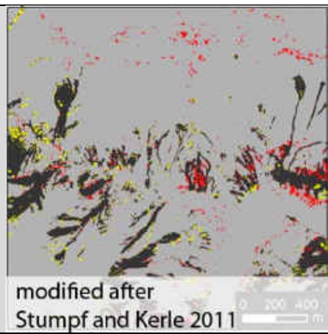
Accuracy level					Alternatives					Coverage					
		100k m^3 volumes	High detection rate for elevation changes > 10 m				Multitemporal LiDAR and SAR			Hundreds of km^2					

Spatial resolution	Temporal resolution	Costs of input data				
Typically 4 times the pixel size of the input image	Minimum a few days			2x SPOT DSMs at 2.3 €/ km^2, 2x Cartosat-1 stereo pair at 2.55 €/ km^2	2x ALOS Prism triplet at 0.41 €/ km^2	

Additional costs for rapid response					Additional costs for processing					Development status				
Processing involves still too much manual adjustments for rapid response							Ground control points (if required)	5000-10000 € for photogrammetric soft-ware						

Estimated elaboration time						Advantages	Limitations
	Weeks for full photogrammetric processing chain		Days with pre-processed DSMs products			• Volume estimation over wide areas possible due to good global availability • High detection rates • Generated DSM are useful for many other applications	• Displacement should exceed 5-10 m • In many cases manual correction of spikes and vegetation effects is necessary

Object-oriented classification of spaceborne images



A13

Sensor type	Platform	Recording system	System names	Contributing institution	Applicable analysis methods	Method Nr.	Data product
Passive optical sensors	Satellite	High resolution - multispectral (GSD<5 m)	IKONOS, Quickbird, World-View 2, Pleiades, Geoeye-1, Rapid-Eye	ITC	Object-oriented image analysis (D4.1 Part A: 4.8)	A13 (see also A7)	Landslide area, (type, number)

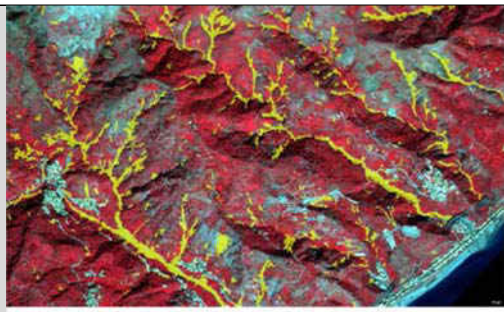
Accuracy level					Alternatives					Coverage					
	Landslide types	Landslide number	Landslide area		Visual interpretation					Hundreds of km^2					

Spatial resolution	Temporal resolution	Costs of input data				
Landslides larger then 10-100 m^2 can be detected	Minimum a few days		7.50-10.50 €/ km^2 for archive data			Free for members of International Charter Space and Major Disasters

Additional costs for rapid response					Additional costs for processing					Development status				
	5-30 €/ km^2			Free for members of the International Charter Space and Major Disasters			5-10k € for professional software		Open source software					

Estimated elaboration time					Advantages	Limitations
		Rule set training/ threshold estimation	Provision of samples for training		• Higher accuracies then pixel-based image analysis • Potential to distinguish individual landslides and landslide types • Sample based adaption of algorithms possible • Input data quickly available after major disasters	• Still very few rule sets available • Difficult adaption of rule sets for different scene characteristics

Object-oriented change detection with spaceborne images


modified after Lu et al. 2011

A14

Sensor type	Platform	Recording system	System names	Contributing institution	Applicable analysis methods	Method Nr.	Data product
Passive optical sensors	Satellite	High resolution - multispectral (GSD<5 m)	IKONOS, Quickbird, World-View 2, Pleiades, Geoeye-1, Rapid-Eye	ITC	Object-oriented change detection (D4.1, Part A: 4.8)	A14 (see also A7)	Landslide area, number (event-based)

Accuracy level

	Landslide types	Landslides number	Landslide area	

Alternatives

Visual interpretation	Pixel-based change detection			

Coverage

Hundreds of km^2					

Spatial resolution	Temporal resolution
Landslides larger then 10-100 m^2 can be detected	Up to daily with satellite programming, often years between suitable images in the archive

Costs of input data

	7.50-10.50 €/ km^2 for archive data, + post-event imagery, typically with additional costs for tasking order			Free with activations of the International Charter Space and Major Disasters

Additional costs for rapid response

	5-30 €/ km^2			Free with activations of the International Charter Space and Major Disasters

Additional costs for processing

		5-10k € for professional software		Open source software

Development status

Estimated elaboration time

		Rule set training/ threshold estimation		

Advantages	Limitations
• Higher accuracies then pixel-based image analysis • Suppression of change noise • Fewer thresholds	• Threshold selection needs considerable user intervention • Often difficult to obtain two images that were acquired under similar conditions • Additional cost for pre-event data

Digital total station surveys

Source: www.geosolution.com

B1

Sensor type	Platform	Recording system	System names	Contributing institution	Applicable analysis methods	Method Nr.	Data product
Active optical sensor	Ground - based	Distance - meters and digital theodolite	Total stations	UNIL	Repeated point-wise measurements (D4.1, Part B: 2)	B1	3D coordinates, 3D displacement

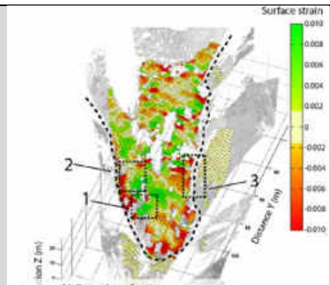
Accuracy level					Alternatives					Coverage					
			cm	mm						Max. range up to 5 km (using prisms)	Site specific				

Spatial resolution	Temporal resolution	Costs of input data				
0.01-1 points/m²	Depending on survey intervals, seconds-years		100-500 €/km²			

Additional costs for rapid response					Additional costs for processing					Development status				

Estimated elaboration time					Advantages	Limitations
					• High accuracy • Temporal and spatial resolution on demand • Considerable maximum range • 3D information • High flexibility • Feasibility of automation of the process •suitable for early warning systems	• Low coverage (point-wise measurements do not provide a complete image of the object) • Intervisibility is required (optical line of sight)

Terrestrial LiDAR scanning



modified after Travelletti et al. 2011

B2

Sensor type	Platform	Recording system	System names	Contributing institution	Applicable analysis methods	Method Nr.	Data product
Active optical sensor	Ground - based	LiDAR	e.g. ILRIS-3D	UNIL	Morphostructural analysis and change detection (D4.1, Part B: 3)	B2	3D coordinates of million points, volumes, displacement, strain

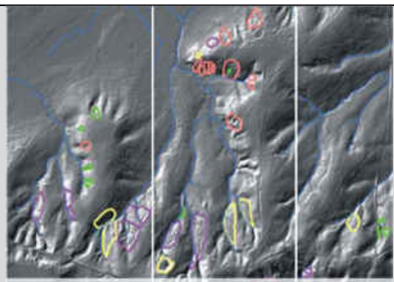
Accuracy level					Alternatives					Coverage					
			cm			GB-InSAR for some applications				max. range up to 1.5 km (typically below 600 m)	Site specific	Local			

Spatial resolution	Temporal resolution	Costs of input data				
10-100 points/m^2	Depending on survey intervals, hours-years				100-500 €/ km^2	3000 €/ km^2 with higher point density

Additional costs for rapid response					Additional costs for processing					Development status				
	Rent of additional equipment	Expert	Transport			Large datasets	Highly specialised software						Commercialized	

Estimated elaboration time					Advantages	Limitations
		Expert interpretation	Point-cloud processing	Hours for scanning	• High resolution and accuracy (centimetre level) • good coverage on steep slopes • 3D information • High flexibility (i.e., easy set-up and portability)	• Relatively low maximum range (< 600m) • Post processing is needed (aligning, filtering, etc.) • Intervisibility is required (optical line of sight)

Airborne LiDAR scanning


modified after Van Den Eeckhaut et al. 2011

B3

Sensor type	Platform	Recording system	System names	Contributing institution	Applicable analysis methods	Method Nr.	Data product
Active optical sensor	Airborne	LiDAR	e.g. Optech ALTM	JRC	Visual interpretation, morphostructural analysis (D4.1 Part B: 4), Object-oriented analysis (D4.3: 3.3 and 3.4)	B3	x, y and z coordinates of million points, areas, volumes, displacement

Accuracy level					Alternatives					Coverage					
		dm	cm							Max. range up to 6 km (typically from 1 up to 3 km)		Local	Regional scale		

Spatial resolution	Temporal resolution	Costs of input data				
0.1- >30 points/m^2	(month) typically years	Higher for higher point densities	0.5 points/ m^2 over large areas, around 100- 300 €/ m^2			

Additional costs for rapid response					Additional costs for processing					Development status				
	Plane	Crew				Large datasets	Highly specialised software					Analysis	Data acquisition	

Estimated elaboration time					Advantages	Limitations
	Expert interpretation		Point-cloud processing	Hours for scanning	• High accuracy • Near nadir viewing • Software tools for post-processing widely available • Useful in vegetated areas (LiDAR pulses may penetrate through canopy) • Major teething problems have been solved by now	• Rather expensive • Data collection can occur beneath clouds and in some haze, but because water absorbs most near infrared light, it will not operate correctly during fog, rain, or snow. • Bad coverage in steep terrain (e.g. cliffs)

SAR distance meters

modified after Norland 2004

C1

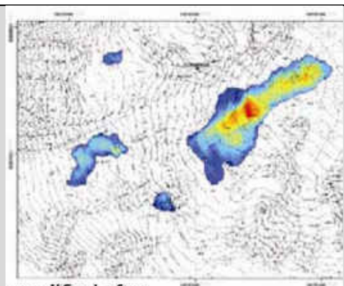
Sensor type	Platform	Recording system	System names	Contributing institution	Applicable analysis methods	Method Nr.	Data product
Active micro-wave sensors	Ground-based	SAR distance - meter	not named	UNIL	Interferometric Radar Distance measurements (D4.1 Part C: 2)	C1	Relative displacements along LOS

Accuracy level					Alternatives					Coverage					
				0.1 mm			EDM but lower accuracy			Up to 5 km distance	Point				

Spatial resolution	Temporal resolution	Costs of input data				
1 point/m^2	Depending on the survey intervals (minutes) - years		+ Corner reflectors	Approx. 50.000€ from SAR hardware		

Additional costs for rapid response					Additional costs for processing					Development status				
n.a.									(green)				Used operationally in EWS, not commercialized	

Estimated elaboration time					Advantages	Limitations
		Installation			• Very High Accuracy (0.1mm) • High Range (up to 5km) • High Temporal Resolution (on demand) • Suitable for Early-Warning System	• Low spatial resolution •point-wise measurement in the line of sight (LOS) • Not 3D-vectors • Intervisibility required • Complex installation

Ground-based SAR (C-band)	 modified after Pieraccini et al. 2006	C2

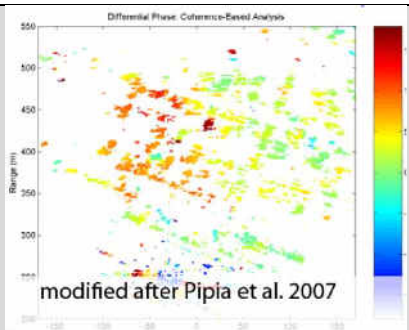
Sensor type	Platform	Recording system	System names	Contributing institution	Applicable analysis methods	Method Nr.	Data product
Active micro-wave sensors	Ground-based	InSAR (C-band)	Doppler radar	UNIFI	Ground-based SAR interferometry (D4.1 Part C: 5)	C2	Interferograms, displacement maps, coherence maps, power images

Accuracy level					Alternatives					Coverage					
				mm		EDM for point-wise measurements				Typically up to 5 km^2 and range up to 4 km	Site specific	Local			

Spatial resolution	Temporal resolution	Costs of input data				
Typical range resolution = 0.5 - 1 m, azimuth resolution (at 500 m distance) = 5 m	Depending on the survey intervals , minutes to months			Similar as Ku-band InSAR (see method C4)		

Additional costs for rapid response					Additional costs for processing					Development status				
				Similar as Ku-band InSAR (see method Nr. C4)				Similar as Ku-band InSAR (see method Nr. C4)						

Estimated elaboration time					Advantages	Limitations
			Hours including setup	Minutes	• Provides areal information • Near real-time • Higher penetration capabilities and less disturbance from vegetation and atmospheric effects than systems operating in X-band or Ku-band	• Measures displacements only along the line of sight (LOS) • Lower accuracy and azimuth resolution than systems operating in X-band or Ku-band

Ground-based SAR (X-band)	 modified after Pipia et al. 2007	C3

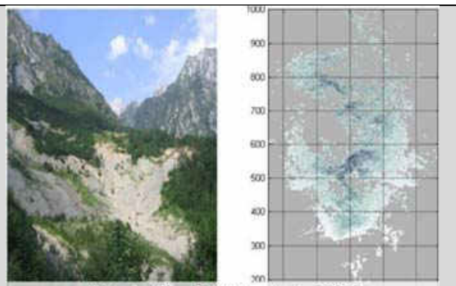
Sensor type	Platform	Recording system	System names	Contributing institution	Applicable analysis methods	Method Nr.	Data product
Active micro-wave sensors	Ground-based	InSAR (X-band)	Doppler radar	UNIFI	Ground-based SAR interferometry (D4.1 Part C: 5)	C3	Interferograms, displacement maps, coherence maps, power images

Accuracy level					Alternatives					Coverage					
				mm		EDM for point-wise measurements				Typically up to 5 km^2 and range up to 4 km	Site specific	Local			

Spatial resolution	Temporal resolution	Costs of input data				
Typically range resolution = 0.5 - 1 m, azimuth resolution (at 500 m distance) ~ 1.5 m	Depending on the survey intervals , minutes to months			Similar as Ku-band InSAR (see method Nr. C4)		

Additional costs for rapid response					Additional costs for processing					Development status				
				Similar as Ku-band InSAR (see method Nr. C4)				Similar as Ku-band InSAR (see method Nr. C4)						

Estimated elaboration time					Advantages	Limitations
			Hours including setup	Minutes	• Provides areal information • Near real-time • Higher penetration capabilities and less disturbance from vegetation and atmospheric effects than Ku-band • Higher accuracy and azimuth resolution than C-band	• Measures displacements only along the line of sight • Lower penetration capabilities and more disturbance from vegetation and atmospheric effects than C-band • Lower accuracy and azimuth resolution than systems operating in Ku-band • More sensitive to atmospheric fluctuations

Ground-based SAR (Ku-band)	 modified after D'Aria et al. 2010	**C4**

Sensor type	Platform	Recording system	System names	Contributing institution	Applicable analysis methods	Method Nr.	Data product
Active micro-wave sensors	Ground-based	InSAR (Ku-band	Doppler radar	UNIFI	Ground-based InSAR (D4.1 Part C: 5)	C4	Interferograms, displacement maps, coherence maps, power images

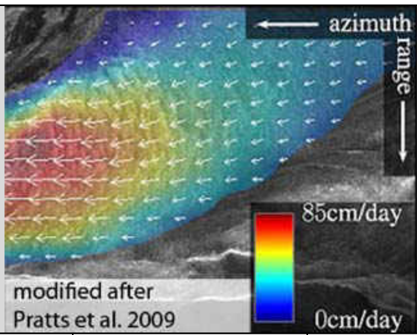
Accuracy level					Alternatives					Coverage					
				mm		EDM for point-wise measurements				Typically up to 5 km^2 and range up to 4 km	Site specific	Local			

Spatial resolution	Temporal resolution	Costs of input data				
Typically range resolution = 0.5 - 1 m, azimuth resolution (at 500 m distance) = 5 m	Depending on the survey intervals , minutes to months			Price per images: few hundreds of €	Low for periodical check, few images repeated for separated intervals	

Additional costs for rapid response					Additional costs for processing					Development status				
		Rent of additional systems if available few thousand €	Transport	Experts few hundred €			Typically less than few thousand of Euros		Very low for permanent and periodic monitoring					

Estimated elaboration time					Advantages	Limitations
			hours including setup	minutes	• Provides areal information • higher accuracy and azimuth resolution than C-band or X-band	• Measures displacements only along the line of sight • lower penetration capabilities and more disturbance from vegetation and atmospheric effects than C-band or X-band

Airborne SAR (multiband)



C5

Sensor type	Platform	Recording system	System names	Contributing institution	Applicable analysis methods	Method Nr.	Data product
Active micro-wave sensors	Airborne	SAR (multiband)	E-SAR, Pi-SAR2	ITC	Interferometry, Image correlation (D4.1 Part C: 4, D4.3: 3)	C5	Mulit-band SAR data, displacement fields

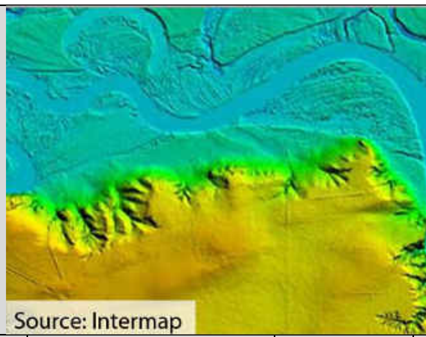
Accuracy level					Alternatives					Coverage		
				mm						10-20 km swath	site specific	Currently only a few prototype systems: http://earth.eo.esa.int/polsarpro/input.html

Spatial resolution	Temporal resolution	Costs of input data				
1 - 3 m	depends on new survey					Prototype

Additional costs for rapid response	Additional costs for processing					Development status				
Prototype	Prototype					Prototype				

Estimated elaboration time					Advantages	Limitations
					• Very high spatial resolution • Potential synergies from simultaneous multiband observation	• Prototype systems

Airborne SAR (X-band)



C6

Sensor type	Platform	Recording system	System names	Contributing institution	Applicable analysis methods	Method Nr.	Data product
Active micro-wave sensors	Airborne	InSAR (X-Band)	STARi3	CNRS	Integration for hazard assessment, DTM differencing (D4.3: 3.3.1)	C6	DSM, DTM

Accuracy level				
		m		

Alternatives				
Few with country wide coverage				

Coverage					
Regional-continental					

Spatial resolution	Temporal resolution
0.65-3.0 m (products usually resampled to 3-5m)	One time slice for European countries (late 90's -2009), but no updates planned at the moment

Costs of input data				
		~20 €/km²		

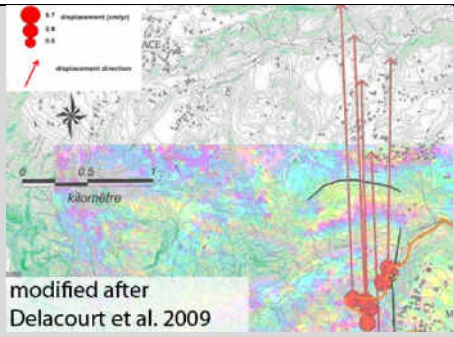
Additional costs for rapid response				
n.a.				

Additional costs for processing				
				Readily pre-processed

Development status				

Estimated elaboration time				
				Data is readily available with full coverage

Advantages	Limitations
• GIS ready high-resolution DTM and DSM with full coverage of Europe	• No multitemporal updates planned • Lossy filtering for DTM creation

Spaceborne SAR interferometry (L-band)	 modified after Delacourt et al. 2009	**C7**

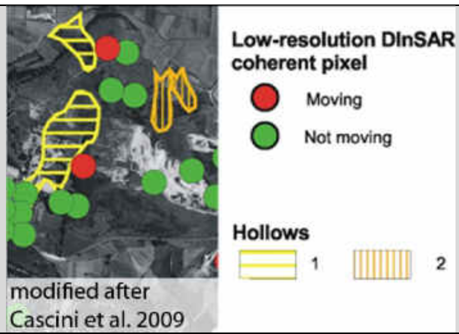
Sensor type	Platform	Recording system	System names	Contributing institution	Applicable analysis methods	Method Nr.	Data product
Active micro-wave sensors	Satellite	InSAR (L-band)	ALOS PALSAR, JERS (historical)	BRGM	Interferometry, (D4.1: Case study 16)	C7	Vertical and E-W components of surface displacement

Accuracy level					Alternatives					Coverage					
			cm							Swath width: 50-100 km					

Spatial resolution	Temporal resolution	Costs of input data				
~10m in XY	35 days			15 ALOS scenes (~3€/km²)		

Additional costs for rapid response	Additional costs for processing					Development status				
Currently ALOS cannot be programmed in an emergency perspective			~15k €				Limitations of the InSAR techniques.	Needs interpretation	Processing technique well established	

Estimated elaboration time					Advantages	Limitations
		2 month after the data- reception			• Retro-analysis of past archive possible on sites without ground instrumentation • Coverage (up to 50-100km) • Image format • Accuracy and precision • Less sensitive to vegetated land cover than C/X-band InSAR • Cost-effective	• Limitations of the InSAR (decorrelation/atmospheric effects) • Adapted for very slow displacements (<dm/yr.) • 1D LOS measurements (several modes or additional information needed for retrieving 3D displacement)

Spaceborne SAR (C-band)		C8

Sensor type	Platform	Recording system	System names	Contributing institution	Applicable analysis methods	Method Nr.	Data product
Active micro-wave sensors	Satellite	InSAR (C-band)	ERS-1/2, Radarsat, ENVISAT SAR	GeoZS	Permanent Scatter (D4.1, Part C: 3.2, D4.3: 3.2.3)	C8	Vertical and E-W components of surface displacement

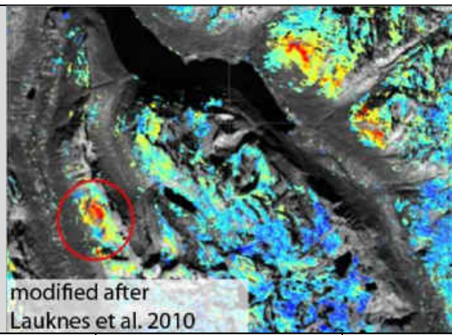
Accuracy level					Alternatives					Coverage					
				mm						Swath width:50-100 km					

Spatial resolution	Temporal resolution	Costs of input data				
XY point wise, LOS ≈ 1mm	24-35 days		More scenes are usually recommended	Min. 15 scenes, 16 €/ km² (Radarsat, programming)		Min. 15 Scenes, 0.6 €/km² (ERS, archive)

Additional costs for rapid response					Additional costs for processing					Development status				
			2 €/ km²	0.2 €/ km²		Over small areas (100 km²) ~ 20 - 35k/ 100 km² for retrospective analysis of up to 7 years			Over large areas (10000 sq.km) ~ 2k €/ 100 km², retrospective analysis for up to 7 years					

Estimated elaboration time					Advantages	Limitations
				Monthly updates are offered by private companies at additional costs	• Fast data processing / low user interaction • High point density in urban areas • High accuracy • Cost-effective, regular updates over large areas • Easy data-integration in standard GIS	• Not applicable in densely vegetated and forested areas • Costly for specific local analysis • Low-reflectivity areas (e.g. smooth surfaces and certain materials). • Temporal sampling limited by satellite repeat-cycles • Only "slow" deformation can be measured (<10 cm/yr in LOS) • Difficult anticipation of PS distribution in an area • SAR data must be acquired by the same satellite

Small baseline spaceborne SAR (C-band)



C9

Sensor type	Platform	Recording system	System names	Contributing institution	Applicable analysis methods	Method Nr.	Data product
Active micro-wave sensors	Satellite	InSAR (C-band)	ERS-1/2, ENVISAT SAR	UNISA	SBAS - Small baseline subset (D4.1: 4.3.1 and Case study 11)	C9	3D reconstruction of landslide displacements

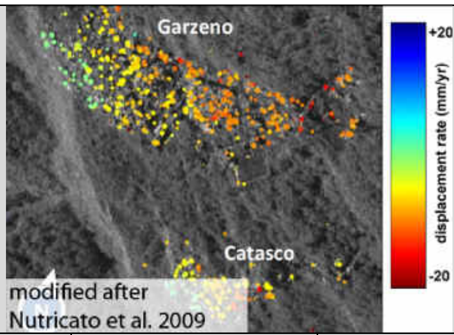
Accuracy level					Alternatives				
				mm					

Coverage					
Swath width:50-100 km					

Spatial resolution	Temporal resolution	Costs of input data				
80 x 80 m^2 for full-resolution data; 10 x 10 m^2 for high-resolution data	35 days					Min. 15 scenes, 0.6 €/km^2 (ERS, archive)

Additional costs for rapid response					Additional costs for processing					Development status				
			2 €/ km^2	0.2 €/ km^2										

Estimated elaboration time					Advantages	Limitations
			3 weeks for a 30 image data-set		• Fast data processing / low user interaction • High point density in urban areas • High accuracy • Cost-effective, regular updates over large areas • Easy data-integration in standard GIS	• Not applicable in densely vegetated and forested areas • costly for specific local analysis • Low-reflectivity areas (e.g. smooth surfaces and certain materials). • Temporal sampling limited by satellite repeat-cycles • Only "slow" deformation can be measured (<10 cm/yr in LOS) • difficult anticipation of PS distribution in an area • SAR data must be acquired by the same satellite

Spaceborne SAR (X-band)	 modified after Nutricato et al. 2009	**C10**

Sensor type	Platform	Recording system	System names	Contributing institution	Applicable analysis methods	Method Nr.	Data product
Active micro-wave sensors	Satellite	InSAR (X-Band)	TerraSAR-X, Cosmo-SkyMed	ITC	Interferometry and DIC (D4.1 Part C: Chapter 4.3.2 , D4.3, 3.3.2)	C10	Surface displacement in the line of sight

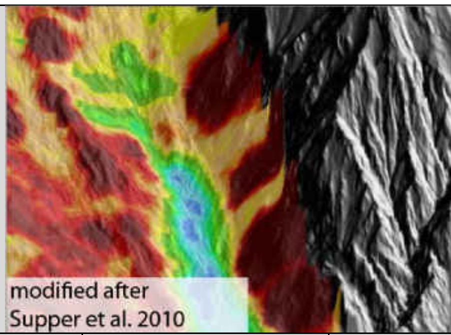
Accuracy level					Alternatives					Coverage					
				mm		C- and L-band				Typically stripmap-mode 30 km x 50 km, scansar-mode 100 km x 150 km					

Spatial resolution	Temporal resolution	Costs of input data				
Spotlight mode 1m, stripmap mode 3m, scansar mode 16 m	TerraSAR-X: 11 days, Cosmo Skymed: 4,5-37h		M(15 scenes) 15.75 - 37.5 €/km²		1 scene in Stripmap mode 1.05-2.50 €/km²	

Additional costs for rapid response					Additional costs for processing					Development status				
			+ 50% of the product price for Cosmo Skymed		Private sector offers high frequency observations, for an area of 100 km² during 1 year in the range of 100k €		High level of expertise needed							

Estimated elaboration time					Advantages	Limitations
			Monthly updates are available	Near-real time data distribution for Cosmo Skymed is possible	• Higher accuracy than L and C-band InSAR • Range of measurable deformation is much higher mm to theoretically about 70 cm per year • Potentially higher point densities • Potential for DIC to obtain horizontal displacement	• Poor sampling in vegetated areas, rapid displacement >1m/year leads to decorrelation • High data costs and few available case studies • X-band is stronger affected by atmospheric effects than L and C-band methods

Airborne geophysics


modified after Supper et al. 2010

D1

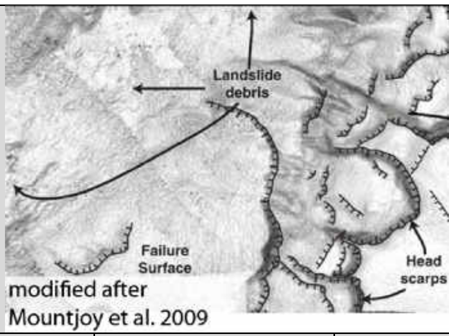
Sensor type	Platform	Recording system	System names	Contributing institution	Applicable analysis methods	Method Nr.	Data product
Active micro-wave sensors	Airborne	Geophysical probe	"Bird"	GSA	(D4.1 Part D: 4, further details in D4.5)	D1	Ground resistivity with depth, soil moisture, gamma-ray, magnetometry

Accuracy level					Alternatives					Coverage					
			50x50 m^2 spatial unit							<10 km^2					

Spatial resolution	Temporal resolution	Costs of input data				
50x50 m^2	Depends on survey intervals		~ 1.9-2 €/ 250 m^2			

Additional costs for rapid response				Additional costs for processing					Development status				
	~ 1.9-2 € / 250 m^2						~ 0.5 €/ 250 m^2						

Estimated elaboration time					Advantages	Limitations
		3 months			• Simultaneous multiparametric survey for large areas • The only remote-sensing method investigating the subsurface • Subject of on-going research within SafeLand	• Limitation by noise of power-supply lines • Terrain roughness and steepness (constant distance of sensor to the ground surface needed) • Limitation by internal 3D geometry in the subsurface • Subject of on-going research within SafeLand

Multibeam seafloor bathymetry		D2

modified after Mountjoy et al. 2009

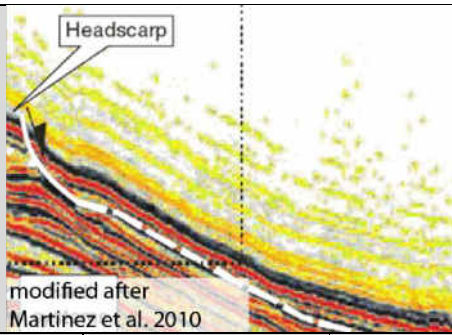
Sensor type	Platform	Recording system	System names	Contributing institution	Applicable analysis methods	Method Nr.	Data product
Sonar + Radar	Offshore vessel and platforms	Bathymetry	Multibeam echosounders & interferometric systems	NGU	(D4.1, part D: 3.1)	D2	Seafloor x, y and z coordinates; volumes; displacement; back-scatter

Accuracy level					Alternatives					Coverage					
	m	dm depending mainly on depth	cm	mm	Hydrographic LiDAR (e.g. Shoal) for shallow waters (up to 70 m)					5.5x - 12x water depth	Site	Local	Regional		

Spatial resolution	Temporal resolution	Costs of input data				
0.01 - 100 points/ m²	depends on survey intervals (hours- days- months- years)		Mainly depending on cost for vessel & input data from sound velocity profile (important for coastal brackish environments)			

Additional costs for rapid response					Additional costs for processing					Development status					
	depending on availability and costs of vessels														

Estimated elaboration time					Advantages	Limitations
			days-weeks		• High resolution and accuracy • Fast data processing / low user interaction • Easy data integration in standard GIS • Spatial and temporal resolution on demand • Generated bathymetry model are useful for many other applications	• Minimum detectable displacement in dm to m scale • Resolution depends on water depths

Offshore seismic surveys		**D3**

Sensor type	Platform	Recording system	System names	Contributing institution	Applicable analysis methods	Method Nr.	Data product
Seismic	Offshore vessel and platforms	2D & 3D high-resolution seismics	Airguns, boomer, sparker	NGU	(D4.1, part D: 3.1)	D3	Seismic lines (2D) / volumes (3D); acoustic impedance

Accuracy level				
	m	dm depending mainly on depth	cm	

Alternatives				
No alternative techniques				

Coverage					
			Regional		

Spatial resolution	Temporal resolution
cm-m	Depends on survey intervals (hours- days- months- years)

Costs of input data				
	Mainly depending on cost for vessel and on target (resolution; 2D or 3D seismics)			

Additional costs for rapid response				
	Depending on availability and costs of			

Additional costs for processing				

Development status				

Estimated elaboration time				
		Month	Days-weeks	

Advantages	Limitations
• Subsurface information • Precise volume calculations with 3D seismics	• Poor data quality on steep seafloor surfaces (>10°) • Resolution depends on water depths

2.2. Remote-sensing of landslides with different velocities

2.2.1. Explanatory text *[UPC]*

The displacement rate of a landslide can be seen as the most critical factor for detection, associated risks and human response. The aim of this section is to guide in the selection of the appropriate remote sensing method to investigate the landslides according to their expected displacement rate. The use of remote sensing techniques in landslide investigations may initially target the detection of previously unknown landslides, including currently active mass movements but also older inactive once. Once the landslide location is known, it will often be necessary to obtain a first, but reliable perception of the landslide characteristics (fast characterization; i.e., the failure mechanism, the progression mechanism, the landslide size and kinematics), and a rapid mapping of the area. Optionally, a long-term monitoring plan might be envisaged to follow the phenomena over time.
Accordingly, in Table 2 the remote sensing methods have been arranged according to their applicability for landslides with different displacement rates and according to the following four tasks:

- **Detection:** Initial recognition of previously unknown landslides from space- or airborne imagery
- **Fast characterization:** Retrieving information on failure mechanism, volume involved, and run-out length
- **Rapid mapping**: Fast semi-automatic image processing for change detection and/or target detection; hotspot mapping
- **Long-term monitoring**: Retrieving time series of deformation/displacement over longer time periods.

Detection of new landslides

Air- and spaceborne remote sensing techniques are important tools for the detection of active and dormant landslide over larger areas. Especially where the terrain characteristics make a direct site access difficult imagery can be used to prioritize areas for further investigations.

The initial detection of first-time slope failures or reactivations at previously unmonitored sites is a difficult and challenging task. Methods quoted in Table 2 are indicated only for *some* or for a *few* cases. Though the number of case studies using satellite radar interferometry, airborne LiDAR and high resolution satellite imaging is constantly increasing, each technique is only appropriate for some landslides (Table 2) and constrained by the displacement rate and other environmental factors. Since the applicability of techniques using airborne metric and non-metric cameras depends mainly on the availability of historical archives and/or recent image acquisitions they are used only occasionally. At present there is no method available covering the whole range of landslide velocities and in most cases detection will only be possible in a post-failure state.

The satellite Radar interferometry (satellite InSAR) is indicated for very slow or extremely slow movements. Beyond these velocities, some problems related to the ambiguity of the signal arise. For instance, if a 5 cm semi wave length is used ($\lambda/2$), a point movement of 10 cm can be disregarded as the phase difference between two epochs is very close to zero (except if some advanced techniques are used). If there is no 'image' of the point between the two situations, one cannot know the exact behaviour, there is an ambiguity. This point has a strong relation with the temporal resolution (or revisiting time) of the available Radar satellites (typically 24 to 35 days, Table 1). If the landslide is moving in the order of $\lambda/2$ or more between two consecutive passes, the Radar techniques will be less applicable.

For the detection of moderate to extremely rapid landslides, the analysis of high resolution satellite imagery is the most useful method as reported in the Table 1. Specifically, analysis of objects or changes in the images from high resolution multispectral sensors has been used. The images frequently come from the IKONOS, Quickbird, World-View 2, Pleiades or Geoeye-1 satellites. Nevertheless, this methodology seems only applicable to few cases for moderate to fast landslides. The information in the images is now unambiguous; however the aspect of the features (objects) may change along the time due to natural factors. The displacements have to be noticeable in order to be measured. The temporal resolution is in the range of days, weeks, or months between consecutive images. Thus, these image analysis techniques are only suitable for certain fast movements.

The airborne LiDAR covers a wide range of velocities (from extremely slow to very rapid landslides). However, in many cases the displacement rate of the landslide will exceed the current stat-of-the art in terms of observation intervals and hence airborne LiDAR is mostly used for observations in the post-failure state.

Effectively, in the literature some cases of successful detection of landslides with airborne LiDAR can be found, although the methodology seems to be strongly case dependent. The basis of the procedure is to compare digital terrain models (DTM) acquired in several epochs. The time elapsed between successive campaigns must be adequate to the phenomena under consideration. LiDAR general purpose flights (for cartographic mapping) are too scarce (once a year at most), and the height of the plane is too high as well. Thus dedicated costly flights must be ordered on demand to monitor adequately a given region. On the other hand, some translational slides can run roughly parallel to the terrain surface, being quite difficult to detect by comparing the DTMs.

Fast characterization to determine the mechanism and the volume

Here, the aim is the fast characterization to determine the mechanism, the area affected by the instability, the volume involved and to distinguish areas or units with different mobility.

In addition to airborne and space-borne sensors, some terrestrial techniques are applicable. Two methods are suitable for fast characterization in many cases: LiDAR (both terrestrial and airborne) and ground based radar interferometry (GB-InSAR). Moreover, the use of satellite InSAR and ground based cameras and video have been applied, but only to a reduced number of cases.

The abovementioned methods do not cover the whole range of velocities, they are typically used for the characterization of slow landslides (extremely slow to slowFor fast characterization of rapid movements, several methods (ground based videos, airborne cameras, terrestrial and airborne LiDAR and high resolution satellite imagery) have been applied. However, real-time observations of such fast moving landslides are generally sparse and most of the techniques are only suited for observations in a post-failure state.

Rapid mapping

After a moving landslide is detected and a first (fast) characterization is made, a rapid mapping procedure allows monitoring the progression of the moving mass, particularly the evolution of their velocity (increasing or decreasing), and providing new input data for updating the forecast of the movement of the landslide. This is essential when urban areas or infrastructures are threatened, though such quick analyses are only feasible for landslides with moderate to slow velocities (< 0.5 mm/sec, approx. 2 m/h). Mapping shortly after a landslide movement has stopped is important at sites where the landslide morphology may change quickly (after some days to a few weeks) due to new landslide activity (e.g. renewed deposition/erosion in an active debris flow channel) or to human activity (removal of blocks fallen on a highway). Capture of the original morphology/topography may be mandatory to carry out a back-analysis of the landslide. At sites where the deposits of several events are accumulated, a rapid mapping after each event allows for a reliable estimation of the event volume.

Most of the techniques quoted for rapid mapping in Table 2, are ground based and applicable to slow-moving landslides (slow to extremely slow). Radar distance-meter measurements (a

ground based method) are the only method that is applicable in a more general way. Ground based radar interferometry (GB-InSAR) and terrestrial LiDAR (TLS) show more limited applications, also in the range of slow velocities. Satellite InSAR is suitable but only to map very slow and extremely slow landslides, because of the low temporal resolution of the technique (24 to 35 days).
Radar distance-meter, ground based video and non-metric cameras are useful for landslides moving with moderate to rapid velocity, though the applicability is case-dependent. For quick landslides (rapid to extremely rapid), terrestrial LiDAR (terrestrial and airborne) and GB-InSAR are in theory capable to provide observation with sufficient temporal frequencies. However, in practice it is very rare that such instruments are in place when such rapid slope failures happen. In contrast VHR satellite imagery can be used repetitively to assess the post-failure state of fast moving landslides at defined intervals.

Long-term monitoring
Once an active landslide is identified at a site and repeated activity in the future has to be anticipated, long-term monitoring may be necessary. Long-term monitoring is required to i) implement an early warning system; ii) to check the effectiveness of the stabilization or other remedial measures and, last but not least; iii) to validate the kinematic model formulated for the landslide.
The most suitable remote sensing techniques for long-term monitoring are ground based techniques such as GB-InSAR, terrestrial LiDAR and ground based non-metric cameras (cf. Table 1). These techniques are applicable in many cases but most suitable for slow (to moderately slow) moving landslides.

GB-InSAR, as any other radar interferometric technique, is not suitable for to monitor rapid landslides; this is due to the possible ambiguity of the signal (as it was mentioned in the section *Detection of new landslides*). Displacements given by SAR sensors require calibration using in-situ measurements, i.e. displacements obtained directly on the landslide (e.g. inclinometric, GPS, surveying or extensometric displacements). Once the calibration is made, GB-InSAR is very useful for monitoring (slow) landslides due to the following reasons: a) it has a high accuracy (0.3 mm), b) a high range (2 km, up to 5 km in special cases), c) a high temporal resolution (5 minutes), which makes it suitable for early-warning and, d) under favourable conditions th advantage that it provides areal information. The latter is the techniques main advantage in relation to in-situ monitoring techniques. As a shortcoming, the measured displacements are primarily the projection of the 3D value on the direction to the sensor, the so-called 'line of sight (LOL) displacement'.

Terrestrial LiDAR (or Terrestrial Laser Scanning) has a coarser temporal resolution than the GB-InSAR, because the acquisition and the post-processing of LiDAR data (aligning, filtering, etc.) requires at least several hours. Typical revisiting period is several months. The main advantages of the technique are: high resolution, good accuracy (centimetre level), large coverage on steep slopes, 3D information, and high flexibility (i.e., easy set-up and portability). Some limitations of TLS are its relatively low maximum range (usually < 700 m) and the requirement of a direct visibility (optical line of sight). However, very recently, the first long-range scanners (up to 3 km) have been released. The above characteristics make TLS very suitable to detect changes in the source area of landslides and to determine the volume of events, particularly in steep slopes.

Ground based non-metric cameras and videos allow an accurate monitoring of displacement at low costs but require visibility of the ground surface (e.g. not in fog or snow). Night video recording of given debris flow channel sections is performed using spots (beams) of white or infrared light. Cameras and videos have a high temporal resolution, regularly up to 24 frames per second, which allows the monitoring of fast moving landslides.
Image recording can be integrated in a monitoring system based on in-situ geotechnical or geophysical sensing (e.g. geophones). In the case of debris flow monitoring, video recording is essential in order to detect flow initiation. Video recording allows for both real-time monitoring and the implementation of a reliable multi-sensor early warning system. However, warning based merely on imagery is only possible when direct visibility of the moving flow is given (e.g. not with fog, snow or heavy rainfall). When this is the case video cameras provide very helpful qualitative information on the general debris flow behaviour. Video or photographic images can also be used for detailed processing and velocimetry analysis. Several debris-flow sites world-wide are being monitored using video cameras, for example, in the European Alps (e.g. Illgraben, Lattenbach) and the Central Pyrenees (Erill la Vall, Senet). The main shortcomings of the method are the requirement of direct (and good) visibility and the relatively high hardware price for video supported tachymeters.

Final remarks
In Table 2 the above mentioned remote sensing techniques are grouped according to their suitability to detect, map and monitor landslides in different velocity ranges.

Table 1: Remote sensing techniques suitable to investigate different landslides according to their expected velocity. The methods summarized here are the ones **suitable in many cases (in bold)** or in some cases (not in bold) as extracted from Table 2. Obviously, there are techniques not shown here that can be used successfully in some particular cases. ^{f} technique applicable during the failure state, ^{pf} technique applicable in the post-failure state.

<table>
<tr><th rowspan="6">Remote sensing techniques for landslide investigation</th><th colspan="7">Landslide displacement rates (mm/sec)</th></tr>
<tr><td>Extremely slow</td><td>Very slow</td><td>Slow</td><td>Moderate</td><td>Rapid</td><td>Very rapid</td><td>Extremely rapid</td></tr>
<tr><td>5 x 10^{-7}</td><td>5 x 10^{-5}</td><td>5 x 10^{-3}</td><td>5 x 10^{-1}</td><td>5 x 10^{1}</td><td>5 x 10^{3}</td><td></td></tr>
<tr><td>16 mm/year</td><td>1.6 m/year</td><td>13 m/month</td><td>1.8 m/hr</td><td>3 m/min</td><td>5 m/sec</td><td>> 5 m/sec</td></tr>
<tr><td colspan="7">Velocity range of common types of landslides</td></tr>
<tr><td colspan="4">Slide and flow in clayey materials (including mudslide and earthflow)</td><td colspan="3">Rockfall
Slide in hard rocks and fragile overconsolidated clays
Shallow slide and debris flow</td></tr>
<tr><td rowspan="3">Detection</td><td colspan="2">Satellite InSAR ^{f}</td><td colspan="5"></td></tr>
<tr><td colspan="2">^{f}</td><td colspan="5">ALS ^{pf}</td></tr>
<tr><td colspan="3"></td><td colspan="4">High resolution satellite image analysis ^{pf}</td></tr>
<tr><td rowspan="4">Fast charac-terization</td><td colspan="2">Satellite InSAR ^{f}</td><td colspan="5"></td></tr>
<tr><td colspan="3">GB-InSAR ^{f}</td><td colspan="4"></td></tr>
<tr><td colspan="3">TLS & ALS ^{f}</td><td colspan="4"></td></tr>
<tr><td></td><td colspan="3">Ground based cameras ^{f}</td><td colspan="3"></td></tr>
<tr><td rowspan="5">Rapid mapping</td><td colspan="2">Satellite InSAR ^{f}</td><td colspan="5"></td></tr>
<tr><td colspan="3">GB-InSAR ^{f}</td><td colspan="4"></td></tr>
<tr><td colspan="3">Radar distance-meter ^{f}</td><td colspan="2">Radar distance-meter ^{f}</td><td colspan="2"></td></tr>
<tr><td colspan="3">TLS ^{f}</td><td colspan="4"></td></tr>
<tr><td></td><td colspan="4">Ground based video and non-metric cameras ^{f}</td><td colspan="2"></td></tr>
<tr><td rowspan="3">Long-term monitoring</td><td colspan="3">GB-InSAR, Satellite InSAR ^{f}</td><td colspan="4"></td></tr>
<tr><td colspan="3">TLS, ALS ^{f}</td><td colspan="4"></td></tr>
<tr><td colspan="4">GB video, metric cameras ,non-metric cameras ^{f}</td><td colspan="3"></td></tr>
</table>

The detection of new (first-time) moving landslides is a real challenge. On one handside, fast landslides (rapid to extremely rapid landslides) are also short-lived, that is to say, they move during a short time span. This makes their discovery very improbable when they are in progress, unless sensors with a very-high frequency of scanning (of a second or less) are used. Such high scan frequencies are uncommon in space- or airborne remote sensing. High scan frequency is only justified locally, for sites where landslide activity is also high, and usually involves ground-based monitoring (i.e., an automatic debris-flow video recording which is triggered by vibration of geophones at the active channel). Such type of monitoring corresponds to a long-term monitoring, in the sense used in this document and cannot be used extensively in a wide area.

On the other hand, common revisiting frequencies of satellite or airborne sensors are high enough for the monitoring of slow moving landslides. Data provided by these techniques require a calibration to filter out the noise component (particularly true for the InSAR techniques). This calibration is done by using in-situ displacements measured on the ground.

The detection of moving landslides and the measurement of their velocity are critical in risk management, but the detection of past landslides (both first-time occurrences and reactivated ones) that moved recently is also a key aspect for risk assessment in the mid- and long-term. Moreover, due to the difficulty of detecting moving landslides, the conventional geomorphological approach, which is based on the experience of past occurrence of landslides, and used for the preparation of hazard maps, can be extended for landslide monitoring by remote sensors. Experience indicates, for example, that the probability of new rockfalls, debris flows or mudslide reactivations is higher in zones where these types of processes have occurred frequently in the past, if stability conditions have not changed significantly . This fact is accounted for in order to anticipate new first-time landslides or future landslide reactivations, and is also applicable to prioritize remote sensor scanning for future landslides in sites or zones where landslides occurred in the recent past. This increases the chance to detect future moving landslides. The detection can be done by comparing data (images or DTMs) obtained in consecutive surveys by any of the methods suitable for detection of moving landslides listed in Tables 1 and 2. It is well-known that lithology of the source zone, failure mechanisms and progression mechanism, i.e.,, landslide type and velocity, are interrelated (this is the underlying link between Tables 2 and 3). For example, slides in clayey formations and in mudslides typically show moderate or slow velocities (<0.5 mm/sec), whereas failures in granular soils and in hard rocks tend to progress as fast mass movements. Hence, for some common types of landslides a qualitative forecast of the velocity of future landslides is possible, by taking into account the landslide type and the lithology of the source zone of past events. This allows to optimize the selection of remote sensing methods for detecting and characterization of future landslides based on landslide type and velocity range anticipated at the site.

2.2.2. Applicability to different displacement rates

Table 2: Applicability of remote sensing techniques for the detection, fast characterization, rapid mapping and long-term monitoring of landslide with different displacement rates [velocities according to *Cruden and Varnes*, 1996].

		Detection			Fast Characterization			Rapid mapping			Long-term monitoring		
Typical velocity		suitable in few cases	suitable in some cases	suitable in many cases	suitable in few cases	suitable in some cases	suitable in many cases	suitable in few cases	suitable in some cases	suitable in many cases	suitable in few cases	suitable in some cases	suitable in many cases
none			B3 (*)			B3 (*)					B3 (*)		
Extremely slow	16 mm /year	C6	B3, C7, C8, C9, C10, D1		A1, B1, C1	C7, C8, C9, C10, D1	B2, B3, C2, C3, C4, D2, D3	B3, D2	B2, C2, C3, C4, C7, C8, C9, C10	B1, C1	A1, A2, A8	C7, C8, C9, C10, B3, D2, D3	A4, B1, B2, C1, C2, C3, C4
Very slow	1.6 m /year	A5, A6, A8, C6, C8, C9	B3, C10, D1, D2, D3		A5, A6, A8, B1, B2 C1, C8, C9,	A1, A2, A12, C10, D1	B2, B3, C2, C3, C4, D2, D3	C8, C9, B3, D2	A4, 8, B2, C2, C3, C4, C10	B1, C1	A5, A6, C8, C9	A1, A4, A8, C10	A2, B1, B2, B3, C1, C2, C3, C4
Slow	13 m /month	A7, A8, A9,A10, A11, A12, A13, A14	B3, D1		A3, A4, A5, A8, A12, A13, B1, B2, C1-C4	A2, D1	B2, B3, C2, C3, C4	10, A13, A14, B3	A4, A8, B2, C2, C3, C4	B1, C1	A3, A10, A12, A13, A14, B3	A4	A2, B1, B2, C1, C2, C3, C4
Moderate	1.8 m /hour	A7, A8, A9, A10, A12	A13, A14, B3		A3, A4, A5, A8, A12, A13, A14 B1, B2, B3, C1-C4	2		A9, A10, A12-A14, B2, B3, C2-C4	A2, A4, B1, C1		A3, A5, A9 A10, A12-A14, A14, B1, B2, B3, C1-C4	A2, A4	
Rapid	3 m /minute	A7, A8, A9, A10, A12	A13, A14, B3		A3, A4, A5, A8, A12, A13, A14 B1, B2, B3, C1-C4			A9, A10, A12-A14, B2, B3, C2-C4	A4, B1, C1		A2, A3, A4, A5, A9,A10, A12-A14, B1, B3, C1		
Very rapid	5 m /sec	A7, A8, A9, A10, A12	A13,A1A4, B3		A3, A4, A5, A8, A12, A13, A14 B1, B2, B3, C1-C4			A9, A10, A12-A14, B2, B3, C1-C4			A3, A5, 9,A10, A12-A14, B3		
Extremely rapid	> 5 m /sec	A7, A8, A9, A10, A12	A13, A14, B3		A3, A4, A5, A8, A12, A13, A14 B1, B2, B3, C1-C4			A9, A10, A12-A14, B2, B3, C1-C4			A3, A5, A9, A10, A12-A14, B3		

(*) if morphology is preserved

Only applicable for post-event investigations

2.3. Remote sensing of different types of movement

2.3.1. Explanatory text *[JRC]*

Within this section, the applicability of different methods according to major landslide types:falls, topples, rotational slides, translational slides, flows, and complex and compound landslides. For each specific landslide type the applicable methods for detection, fast characterization, rapid mapping and long-term monitoring is provided. The focus is put on the most suitable methods (columns 'suitable in most cases' and 'suitable in some cases' in Table 3), although it should be noted that also less suitable techniques can provide good results in specific cases. At the end of this section, some general conclusions are provided.

Falls

Generally, it is difficult to ***detect*** falls with remote sensing technologies. In a few cases visual interpretation of airborne LiDAR (method B3) can help to detect new falls.
Also for ***fast characterization*** the number of useful techniques is limited. It is advised to use ground-based LiDAR (B2), while also airborne low-cost non-metric cameras (photogrammetric analysis and visual interpretation; A8), ground-based distance meters and total stations (B1) or ground- based SAR distance meters (C1) can provide reasonable results in a limited number of cases.
The recommended techniques for ***rapid mapping*** and ***long-term monitoring*** are similar, and consist of ground-based methods such as distance meters and total stations (B1), LiDAR (B2) or SAR distance meters (C1), but also C-, X-, and Ku-band InSAR (C2, C3, C4). In some cases image velocimetry from ground-based video cameras (A4) is useful.

Topples

Table 3 shows some similarities for the treatment of falls and topples. Similar to falls, ***detection*** remains difficult and only visual interpretation of airborne LiDAR (B3) is recommended.
For ***fast characterization*** the number of useful remote sensing techniques is limited. It is recommended to use ground-based LiDAR (B2), while also ground-based distance meters and total stations (B1) or ground- based SAR distance meters (C1) can provide reasonable results in a limited number of cases.
The suitable techniques for ***rapid mapping*** and ***long-term monitoring*** are similar and the same as those applicable for falls. Those are ground-based methods such as distance meters and total stations (B1), LiDAR (B2) or SAR distance meters (C1), but also C-, X-, and Ku-band InSAR (C2, C3, C4). In some cases also image velocimetry from ground-based video cameras (4A) is useful.

Rotational slides

For ***detection*** of rotational slides, visual interpretation of LiDAR derivatives (B3) is recommended. Apart from that method also medium resolution optical satellite imagery for pixel- or object-based change detection (A10, A14) or different techniques using satellite L-, C-, and X-band InSAR (C7, C8, C9, C10) can be used.

Several techniques are suitable for ***fast characterization*** of rotational slides. These include stereophotogrammetric generation of multitemporal DTMs from high resolution panchromatic satellite imagery and subsequent differencing of the DTMs (A12); ground-based and airborne LiDAR (B2, B3), or some applications using ground-based C-, X-, and Ku-band InSAR (C2, C3, C4) or satellite X-band InSAR (C10). In some cases also satellite L- or C-band InSAR (C7, C8, C9) can be applicable.

Rapid mapping of rotational slides is difficult. The most optimal remote sensing techniques are mainly ground-based and only applicable in some cases. They include video velocimetry (4), distance meters and total stations (B1), LiDAR (B2), SAR distance meters (C1) and C-, X- and Ku-band InSAR (C2, C3, C4). Apart from these ground-based techniques, Satellite X-band InSAR (C10) can be suitable.

Finally, for ***long term monitoring*** the use of ground-based and airborne LiDAR (B2, B3) and ground-based and satellite C-, X-, Ku-, and L-band InSAR (C2, C3, C4, C7, C8, C9, C10) is recommended in many cases. In some cases other ground-based techniques such as digital image correlation of terrestrial photographs acquired from non-metric cameras (A2), video velocimetry (A4), distance meters and total stations (B1) or SAR distance meters (C1) can provide good results. Recently, good results were also obtained with object-based change detection using medium resolution optical satellite imagery (A14).

Translational slides

Remote sensing techniques recommended for translational slides are often similar to those recommendedfor rotational slides. However, both satellite- and ground-based InSAR perform a little less satisfactory for detection and fast characterization, while for long term monitoring only satellite InSAR seems to perform less satisfactory.

For ***detection*** of translational slides visual interpretation of LiDAR derivatives (B3) or ground-based distance meters and total stations (B1) are recommended. Apart from that also medium resolution optical satellite imagety for pixel- or object-based change detection (A10, A14) can provide successful results. As mentioned above, compared to rotational slides satellite L-, C- and X-band InSAR (C7, C8, C9, C10) seem less applicable.

Fast characterization is more difficult for translation slides than for rotational slides. The following methods provide only in some cases good results: stereo-photogrammetric generation of multi-temporal DTMs from high resolution panchromatic satellite images and subsequent differencing of the DTMs (A12), ground-based and airborne LiDAR (B2, B3), or some applications using ground-based C-, X-, and Ku-band InSAR (C2, C3, C4). In few cases also satellite L-, C-, and X-band InSAR (C7, C8, C9, C10) can be applicable.

As for rotational slides ***rapid mapping*** of translation slides is difficult, and the best techniques are ground-based and only suitable in some cases. They include video velocimetry (A4), distance meters and total stations (B1), LiDAR (B2), SAR distance meters (C1) and C-, X-, and Ku-band InSAR (C2, C3, C4).

Suitable techniques for ***long term monitoring*** are digital image correlation of terrestrial photographs acquired from non-metric cameras (2), ground-based and airborne LiDAR (B2, B3) and ground-based C-, X- and Ku-band InSAR (C2, C3, C4). In some cases also other ground-based techniques such as video velocimetry (4), distance meters and total stations (B1) or SAR distance meters (C1). In some cases also object-based change detection using medium resolution optical satellite imagery (A14) and satellite L- and C-band InSAR (C7, C8, C9) enable monitoring translational slides.

Flows

Optimal remote sensing techniques for detection, fast characterization, rapid mapping and long-term monitoring of translational slides also appear the best techniques for flows.

For ***detection*** of flows visual interpretation of LiDAR derivatives (B3) is recommended. Apart from that also medium resolution optical satellite imagery for pixel- or object-based change detection (A10, A14) can provide successful results. Hence, in contrast to translational slides, ground-based distance meters and total stations are not recommended. For the ***fast characterization*** of flows stereophotogrammetric generation of multitemporal DTMs from high resolution panchromatic satellite imagery and subsequent differencing of the DTMs (A12) or ground-based and airborne LiDAR (B2, B3) can be useful. However, it should be considered that involved volumes need to exceed the uncertainties of the measurements and for example for shallow debris flows that might not necessarily be the case. For the monitoring of channels in some cases ground-based C-, X- and Ku-band InSAR (C2, C3, C4) can be applicable. ***Rapid mapping*** of flows is difficult, and best techniques are ground-based and only suitable in some cases. They include video velocimetry (A4), distance meters and total stations (B1), LiDAR (B2), SAR distance meters (C1) and C-, X-, and Ku-band InSAR (C2, C3, C4).

Finally, for ***long term monitoring*** ground-based LiDAR (B2) is suitable in many cases. If not, alternatives can be digital image correlation of terrestrial photographs acquired from non-metric cameras (A2), ground-based video velocimetry (A4), object-based change detection using medium resolution optical satellite imagery (A14), ground-based distance meters and total stations (B1), airborne LiDAR, ground-based SAR distance meters (C1) or satellite L- and C-band InSAR (C7, C8, C9).

Complex landslides

Complex and compound landslides have most suitable remote sensing techniques in common with rotational slides.

For ***detection*** of rotational slides visual interpretation of LiDAR derivatives (B3) is recommended. Apart from that also medium resolution optical satellite imagery for pixel- or object-based change detection (A10, A14) or different techniques using satellite L-, C-, and X-band InSAR (C7, C8, C9, C10) can be used. ***Fast characterization*** is in many cases possible with Satellite X-band InSAR (C10). Stereophotogrammetric generation of multitemporal DTMs from high resolution panchromatic satellite imagery and subsequent differencing the DTMs (A12), ground-based and airborne LiDAR (B2, B3), or some applications using ground-based C-, X-, and Ku-band InSAR (C2, C3, C4) or satellite L- and C-band InSAR (C7, C8, C9) can, in some cases, be alternative techniques . The effectiveness of airborne geophysics (D1) for characterization of subsurface conditions is currently under investigation at one of the SafeLand test sites [*Supper et al.*, 2009].

Rapid mapping of complex and compound landslides is difficult. The most optimal techniques are ground-based and only applicable in some cases. They include video velocimetry (A4), distance meters and total stations (B1), LiDAR (B2), SAR distance meters (C1) and C-, X-, and Ku-band InSAR (C2, C3, C4).

LiDAR and InSAR are recommended for ***long-term monitoring*** of complex landslides. In many cases ground-based and airborne LiDAR (B2, B3) or some applications using ground-based C-, X-, and Ku-band InSAR (C2, C3, C4) and satellite X-band InSAR (C10) provide good results. Alternatives are digital image correlation of terrestrial photographs acquired from non-metric cameras (A2), ground-based video velocimetry (A4), object oriented change detection using medium resolution optical satellite imagery (A14), ground-based distance meters and total stations (B1), airborne LiDAR, ground-based SAR distance meters (C1) or satellite L- and C-band InSAR (C7, C8, C9). If airborne geophysical surveys (D1) can be recommended for the monitoring of large complex landslide is subject of a current SafeLand case study [*Supper et al.*, 2009]

Some general observations

Offshore methods such as bathymetry (D2) and high-resolution seismics (D3) are in many cases applicable for the detection, fast characterization and long-term monitoring of a wide range of different <u>submarine</u> landslide types. In a few cases bathymetry can be applied for rapid mapping of different landslides types. The evaluation here refers to the offshore application and therefore cannot be directly compared to the methods in the terrestrial domain. Table 3 shows that the optimal remote sensing techniques for the monitoring of submarine landslides are highly similar to those applied for terrestrial falls and topples on the one hand side, and for slides, flows and complex landslides on the other hand. For ***detection, fast characterization, rapid mapping*** and ***long-term monitoring*** LiDAR and InSAR, both ground-based as well as airborne, seem to have the highest possibility to success. However, the possibilities of optical sensors should not be neglected.

2.3.2. Applicability to different landslide types

Table 3: Applicability of remote sensing techniques for the detection, fast characterization, rapid mapping and long-term monitoring of different landslide types.

	Detection			Fast Characterization			Rapid mapping			Long-term monitoring		
Landslide types	suitable in few cases	suitable in some cases	suitable in many cases	suitable in few cases	suitable in some cases	suitable in many cases	suitable in few cases	suitable in some cases	suitable in many cases	suitable in few cases	suitable in some cases	suitable in many cases
Fall	B3, 7	D2, D3		A8, B1, C1, D2, D3		B2	D2	A4	B1, B2, C1, C2, C3, C4 precursory	A1 ,A5, B3, D2, D3	A4	B1, B2, C1, C2, C3, C4 precursory
Topple	B3, 7	D2, D3		B1, C1, D2, D3		B2	D2	A4	B1, B2, C1, C2, C3, C4 precursory	A1, A5, B3	A4	B1, B2, C1, C2, C3, C4 precursory, D2, D3
Rotational slide	A6-A9, A12, A13, C6	A10, A14, C7, C8, C9, C10, D2, D3	B3,	A2, A5, A6, A8, A13, B1, C1	C7, C8, C9,	A12, B2, B3, C2, C3, C4 C10, D2, D3	A8-A10, A14 C7, C8, C9, B3	A4, B1, B2, C1, C2, C3, C4, C10		A1, A5, A6, A8, A10, A12, A13	A2, A4, A14, B1, C1	B2, B3, C2, C3, C4, C7, C8, C9, C10, D2, D3
Translational slide	A6-A13, C6, C7, C8, C9, C10,	A10, A14, D2, D3	B1, B3,	A2, A5, A6, A8, A13, B1, C1, C7, C8, C9, C10	A12, B2, B3, C2, C3, C4, D2, D3		A8-A10, A14, C7, C8, C9, C10, B3, D2	A4, B1, B2, C1, C2, C3, C4,		A1, A5, A6, A8,A10, A12, A13	A4, A14, B1, C1, C7, C8, C9	A2, B2, B3, C2, C3, C4, D2, D3
Flow	A6-A9, A12, A13, C6, C7, C8, C9, C10	A10, A14, D2, D3	B3,	A2, A3, A5, A6, A8, A13, B1, C1, C7, C8, C9, C10, D2, D3	12, B2, B3, C2, C3, C4		A8-A10, A14, B3, C7, C8, C9, C10, D2	A4, B1, B2, C1, C2, C3, C4		A1, A3, A5, A6, A8,A10, A12, A13	A2, A4, A14, B1, B3, C1, C7, C8, C9	B2, D2, D3
Complex landslide	A6-A9, A12, A13, C6	A10, A14, C7 C8, C9, C10, D2, D3	B3	A2, A5, A6, A8, A13, B1, C1, D1*, D2, D3	A12, B2, B3, C2, C3, C4, C7, C8, C9,	C10	A8-A10, A14, B3, C7, C8, C9, C8, D2	A4, B1, B2, C1, C2, C3, C4, C10		A1, A5, A6, A8, A10, A12, A13, D1*	A2, A4, A14, B1, C1, C7, C8, C9	B2, B3, C2, C3, C4, C10, D2, D3

Note: D1 was still under evaluation within the SafeLand project when this document was finished

2.4. Remote sensing of landslides on different scales

2.4.1. Explanatory text ***[CNRS]***

Within this section, the applicability of different remote-sensing technologies and processing methods is according to different analysis scales (***micro-scale*** e.g. <1:1000 to 1:5000; ***meso-scale*** e.g. > 1:5.000 to < 1:10.000; ***macro-scale*** e.g. > 1:10.000 to 1:100.000). For each task and scale of analysis, the applicable methods are provided. The focus is put on the most suitable methods (i.e. columns ‘suitable in many cases’). At the end of this section, some general conclusions are provided.

Table 4 shows many similarities for ***detection*** and ***fast characterization***; the same type of products and processing methods can be used for the recognition of new landslides and for retrieving information on their type and geomorphological characteristics. At **micro-scales**, VHR imagery (passive sensors) from airborne- or satellite-platforms can be used to characterize the landslide types, while at **meso- and macro-scales**, mainly products from satellite platforms (both passive and active sensors) are recommended. Ground-based measurements are not recommended for such type of applications due to their limited spatial coverage. At all scales, visual interpretation (A7) and photogrammetric analysis (A1-A6, A8, A11, A12) are by far the most commonly used methods. Currently under ongoing research is the use of object-based classification methods (A13, A14) to delineate landslide types on several type of imagery, and the combination of multi-source data (e.g., images and topographical information, fusion of different images).

For ***rapid mapping***, optical imagery acquired from UAV and airborne-platforms are the main sources of information. In most cases, rapid mapping is limited to a small spatial coverage and thus applied at ***micro-scales***. In some cases, on-demand airborne LiDAR is recommended but its applicability is often limited due to budget constraints. In some cases, if the region to be mapped is small, ground-based technologies can be useful.
Again, visual interpretation (A7) and photogrammetric analysis (A1-A6, A8, A11, A12) are the most commonly used methods for the processing of data acquired from passive sensors. For the processing of LiDAR point clouds, filtering and derivation of topographical information (slope, aspect, etc.) combined with a visual interpretation are the most commonly used methods.

For ***long-term monitoring***, the number of useful remote-sensing techniques is more important. It is recommended to use airborne and ground-based LiDAR, ground-based InSAR and VHR ground-based optical imagery at ***micro-scales***. In some specific cases, VHR radar products (< 2.5 m) and optical imagery might be used. It is recommended to use image correlation techniques, interferometric techniques and scattering techniques to process the data and obtain displacement maps. The processing needs very good alignment and co-registration of the sequence of images. It is, therefore, not a straightforward method for non-specialists. At **meso- and macro-scales,** high-resolution optical and radar data (> 5m to < 20 m resolution) might be used; the detected displacement rates depend on the spatial resolution of the data and the velocity of the landslide. The same type of processing techniques as for the micro-scale are recommended.

2.4.1. Applicability at different observation scales

Table 4: Applicability of remote sensing techniques for the detection, fast characterization, rapid mapping and long-term monitoring of landslides at different observation scales.

	Detection			Fast Characterization			Rapid mapping			Long-term monitoring		
Scale	suitable in few cases	suitable in some cases	suitable in many cases	suitable in few cases	suitable in some cases	suitable in many cases	suitable in few cases	suitable in some cases	suitable in many cases	suitable in few cases	suitable in some cases	suitable in many cases
1:1000 (and larger)	A7, A8, C7, C8 C9,		A9, B3, D2, D3	A1-A3, A5, A6, A8, B1, C1, C7, C8, C9		B2, B3, C2, C3, C4, D2, D3	A4, A8, B3, C7, C8, C9, D2		B1, C1, C2, C3, C4	A1, A3, A5, A6	A4, A8	A2, B1, B2, B3, C1, C2, C3, C4, D2, D3
1:5000	A7, A8, A13, C7, C8	A3, A14, C9, C10	B3, D2, D3	A5 ,A6, A8, B1, C1, C7, C8	C9, C10	B2, B3, C2, C3, C4, D2, D3	A8, A14, B3, C7, C8, C9, D2	C1, C10	B1, C2, C3, C4	A3, A5, A6, A14	A2, A8, B1, C1, C7, C8	B2, B3, C2, C3, C4, C9, C10, D2, D3
1:10000	A7, A8, A13, C6	A14, C7, C8, C9, C10	B3, D2, D3	A5, A6, A8, A12, A13, B1	B2, C7, C8, C9, C10	B3, D2, D3	A8, A14, B3, C7, C8, C9, D2	B1, C10		A5, A6, A13	A8, A14, B1	B2, B3, C7, C8, C9, C10, D2, D3
1:25000	A7, A8, A13, C6	A14, C7, C8, C9, C10	B3, D2, D3	A5, A6, A12, A13	B2, B3, C7, C8, C9, C10, D2, D3		A8, A14, B1, B3, C7, C8, C9, D2	C10		A5, A6, A8, A12, A13, B1	A14, B2	B3, C7, C8, C9, C10, D2, D3
1:50000	A7, A9, A10, A11, A12, A13, C6	A14, C7, C8	B3, D2, D3	A1, A12, A13, B3	C7, C8, D2, D3		A9, A10, 14, B3, C7, C8, C10			A10, A11, A12, A13	14	B3, C7, C8, C10,
1:100000	A9,A10, A12, C7, C8			B3, C7, C8			A9, A10, 14, B3			A10, A14, C10	B3, C7, C8,	
1:250000				B3			B3			B3		

2.5. Application of remote sensing techniques in the landslide risk management cycle

2.5.1. Explanatory text ***[ITC]***

Optimal decisions on suitable observation technologies and strategies should not be purely based on knowledge about the landslide process but must be elaborated in the local and regional context. This should include aspects such as the hazard concerned, the risk involved and the recent history of a particular place. Since such aspects are complex it is not practical to provide a detailed strategy for each possible case but the main dimensions of the interrelationships between remote sensing observations and risk management are highlighted in the following. As a conceptual framework we adopt the risk management cycle and highlight the relevance of the remote sensing technologies described in this document within its different phases. The main phases of risk management can be defined as ***prevention*** (***mitigation)***, ***preparedness***, ***response*** and ***recovery*** [*Alexander*, 2002]. Decisions about the optimal observation strategies for a particular area should ideally be based on a thorough hazard and risk assessment, which incorporates all previous observations and experience (cf. Figure 6).Consequently, priority for more detailed observations, both in the spatial and the temporal realm, should be given to areas with higher risks.

Preparedness describes the ability of a community to anticipate a natural hazard and put established plans and procedures into action. Landslide hazard and risk maps are important tools to raise awareness for more susceptible areas, whereas remote sensing derived data (e.g. DTM) provide essential input for the elaboration of such maps (D4.3, Chapter 4). Remote sensing also plays an important role for reliable weather forecasts which are essential to anticipate, for example, the potential occurrence of rainfall triggered landslides.
The ***detection*** and ***fast characterization*** of unstable areas with spaceborne SAR and ground-based LiDAR techniques are relevant tools to quickly understand the nature of newly developing landslides. Several ground-based photogrammetric and radar techniques (A2, A3, A4, B1, B2, C1, C2, C3, C4) are available for observations with sufficient high temporal frequencies to *integrate them into early warning systems* (this is described in detail in deliverable D4.8 “Guidelines for monitoring and early warning systems in Europe – Design and required technology”). Depending on the adopted system observations can be repeated in intervals of hours (ground-based), days (SAR and optical space-borne) or years (e.g., photogrammetry), whereas for ***long-term monitoring*** the observations from the different time intervals can be combined to optimally reconstruct the history of the landslide and increase preparedness for anticipated future scenarios. As illustrated in Figure 6 long-term monitoring programs (e.g., InSAR, LiDAR) can be useful to capture epochs of acceleration, anticipate critical failures and to adjust the observation strategy if precursory signals have been detected.

For the **response** during and after major natural disasters the primary tasks are to rescue people, fulfil their basic needs and to assess and secure the status of important infrastructure. Remote sensing has already become an essential tool to quickly obtain information about the distribution and severity of caused damages, the status of infrastructure or the locations of displaced people. A quick delivery of information is essential in this context and limits the applicability of techniques involving considerable time for data collection and/or processing. Yet, it also has to be noted that the analyses should aim at exploiting all data becoming available during the disaster response (Table 5). As a consequence of international initiatives for remote sensing and disaster response the availability of remote sensing data is increasingly good after major events, but also initiatives on the local, regional and national level should aim at fast and dense data acquisition directly after an event (Figure 6).

Figure 3: Debris slide burying houses and blocking a road as seen in Geoeye-1 imagery recorded shortly after a major landslide event in Brazil, January 2011. Source: GoogleEarth

Slope failures which occur during large triggering events are typically rapid and extremely rapid moving landslides. This largely constrains the possible techniques for ***detection*, *fast characterization*** and ***rapid mapping*** in disaster response to data from optical satellites and airborne sensors (Figure 3). Their visual interpretation is the most common strategy in practice.

SAR data may provide additional information [*Voigt et al.*, 2007] and is especially useful if cloud-cover hinders image acquisition by optical sensors. However, SAR data is generally more difficult to interpret than optical data. SAR data is increasingly used to assess building damage [e.g. *Dell'Acqua et al.*, 2010] or map flooded areas (http://www.zki.dlr.de/map/1934) and more robust results have been reported when SAR and optical imagery are combined [*Brunner et al.*, 2010; *Chini et al.*, 2009]. However, such methods have not yet been tested for post-failure detection of landslides.

Major natural disasters in the recent past illustrated the availability of VHR satellite remote sensing data within hours after an event (e.g., http://supersites.earthobservations.org/main.php). Several approaches have been proposed or are currently under development for efficient post-disaster damage mapping [see review in *Brunner*, 2009; *Kerle*, 2010]. Though a number of studies propose workflows for more efficient event-based landslide mapping based mainly on optical data [*Borghuis et al.*, 2007;

Di et al., 2010; *Lu et al.*, 2011; *Martha et al.*, 2010; *Mondini et al.*, 2011; *Park and Chi*, 2008; *Stumpf and Kerle*, accepted; *Yang and Chen*, 2010] none of the corresponding techniques is currently in use by any of the remote sensing oriented disaster response agencies (e.g., DLR-ZKI, UNOSAT, SERTIT, JRC). Partly this is attributed to the more humanitarian focus of these institutions but it also may be related to difficulties in fast and flexible implementations of proposed methods for optical data. Differencing of pre- and post-event airborne LiDAR data (Table 4, B3) could in principal provide very accurate estimates of affected areas and volumes involved. However, considering the time-frame for an aerial survey and the processing time for large point cloud datasets it seems at present only feasible for smaller selected areas. The employment of UAVs for image acquisition in contrast is more flexible, the first systems incorporating LiDAR sensors are already available [*Eisenbeiss*, 2010] and as the technology evolves, UAVs will probably gain more relevance for disaster response in the near future.

Besides institutionalized efforts for remote sensing-based production of emergency response maps [see *Kerle*, 2010 for an overview on the Indonesia earthquake 2006] there has been an increasingly large interest in tools that enable collaborative map creation by non-experts and volunteers to react upon major disasters. Map creation by laymen, also entitled as neogeography [*Turner*, 2006] or crowdsourcing can yield geographic databases with considerable detail and spatial accuracy [*Girres and Touya*, 2010] and generally profits from knowledge of local communities [*de Leeuw et al.*, 2011]. Though such tools are not remote sensing techniques in a classical sense as such and even though a lot of further research is still needed to understand expectable information content and accuracy of crowd source maps, it can be expected that they will gain an increasingly important role in emergency response [*Goodchild*, 2010]. Figure 4 visualizes an emergency response map for flooding and debris flow events in January 2010 in the Cuzco region Peru based on an open-source crowd sourcing platform. The consideration of such data and their further exploration for landslide disaster response in the European context is highly recommended.

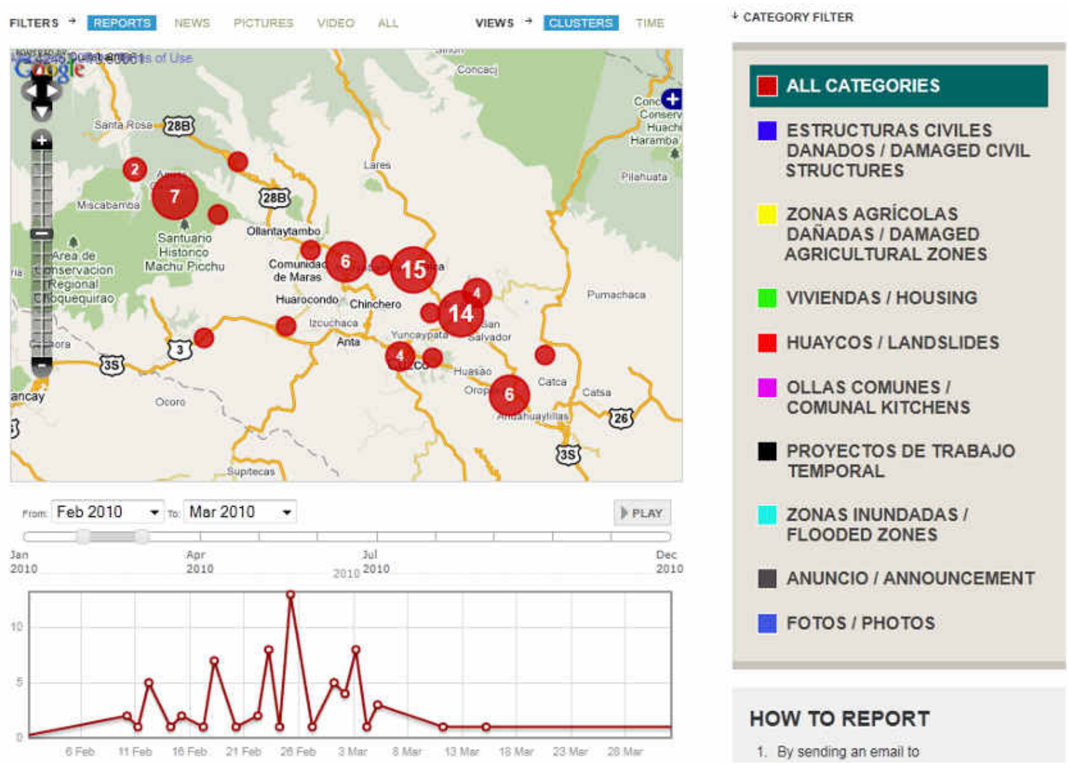


Figure 4: Emergency response map for the flooding and debris flow events in January 2010 in the Cuzco region Peru. The map is based on the open source mapping platform Ushahidi and includes several reports on the occurrence of debris flows. Note that the graph at the bottom visualizes amount and temporal timing of the incoming information to the platform, i.e. how much information is gathered when. Source: http://www.gawana.com/peru/ushahidi/

The **recovery** phase follows and overlaps the disaster response and the application of remote sensing is probably the least developed for this phase [*Joyce et al.*, 2009]. As illustrated in Figure 6 high repetition rates become less important in this phase and the focus should gradually move towards data acquisition on a regular base and for long-term planning. Techniques which demand longer processing time can gradually be applied to ***detect*** previously undiscovered or non-existing slope instabilities and especially InSAR and Airborne LiDAR provide sufficient precision to also discover subtle deformation. The results form techniques of previous ***rapid mappings*** can be enhanced as more (and/or better) imagery becomes available.

Information about displaced volumes is interesting in order to estimate the amount of debris which needs to be removed during the recovery or in order to obtain first estimates on the stability of formed landslide dams. Such tasks can be considered as ***fast characterization*** and stereo-photogrammetric and LiDAR techniques are especially useful here. The observation strategy during the recovery phase should already incorporate plans for ***long-term monitoring***.

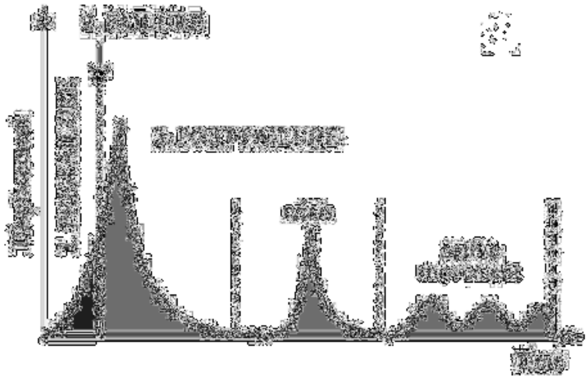


Figure 5: Classification of landslides according to their movement phase [*van Asch et al.*, 2007], modified after [*Vaunat et al.*, 1994].

As illustrated in Figure 5 initial slope failures often proceed in reactivations and large earthquakes can, for example, raise the probability for further landslides in following years [e.g. *Saba et al.*, 2010]. Unstable areas should already be identified during the recovery phase to avoid the (re-)construction in hazardous areas. Especially SAR and LiDAR systems are interesting tools to provide repeated measurements before in-situ monitoring devices may be installed. In order to better understand the general landscape changes, secondary long-term effects of the landslides and complex interaction between the mass-wasting processes and the regional ecosystem it is recommendable to consider the use of time-series from optical sensors as well [*Lin et al.*, 2005; *Rau et al.*, 2007]. The generally enhanced availability of remote sensing data after major events may thereby provide a good starting point for sustainable, well planned image acquisition campaigns.

The aid remote sensing can provide for the **prevention** of landslide disasters is twofold: (1) the collection of landslide inventory-related variables and the provision of information on factors conditioning hazards and risks is the main task; this is described in depth in the SafeLand deliverable D4.3. (2) Another important contribution is to accompany engineering mitigation measures; in most cases such efforts will be relatively local and require remote sensing techniques that provide high accuracy and precision. Such applications may, for example, include 3D measurements after and before slope modifications, or measurements of residual displacements after and during remedial engineering. Therefore, Table 5 lists mainly techniques that locally allow a ***fast characterization*** of the surface and of the involved volumes, and/or allow a precise ***rapid mapping*** and ***monitoring*** of displacements at known hotspots.

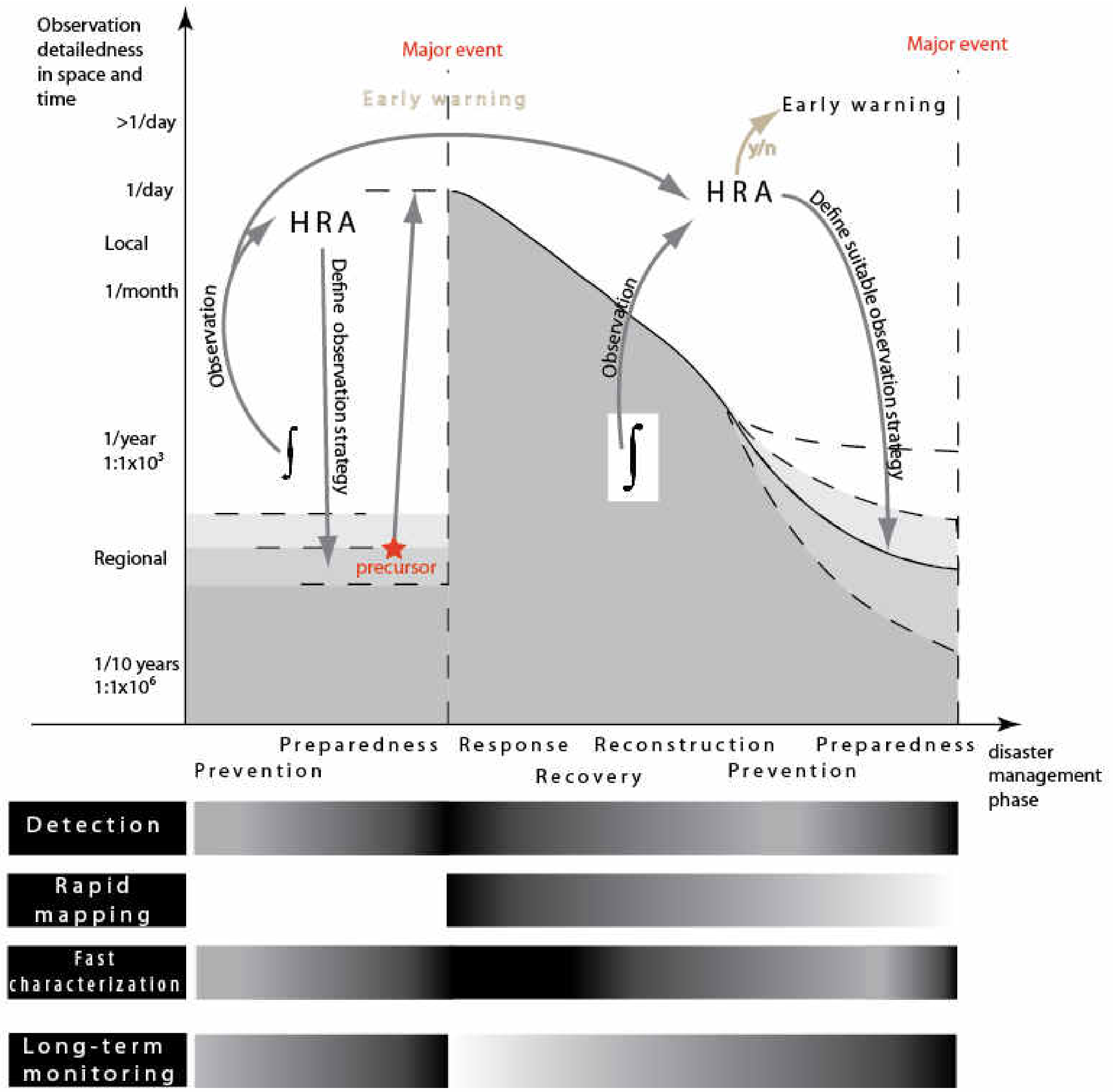


Figure 6: Abstraction of the interrelationships between risk management strategies (HRA = hazard and risk assessment) and observation strategies. The shading of the bars below the graphic gives an indication of the importance of different tasks during the different management phases.

2.5.2. Applicability within phases of the risk management cycle

Table 5: Applicability of remote sensing techniques for the detection, fast characterization, rapid mapping and long-term monitoring of landslides during different phases of the risk management cycle.

	Detection			Fast Characterization			Rapid mapping			Long-term monitoring		
Steps in the RMC	applicable in few cases	suitable in some cases	ideal in many cases	applicable in few cases	suitable in some cases	ideal in many cases	applicable in few cases	suitable in some cases	ideal in many cases	applicable in few cases	suitable in some cases	ideal in many cases
Disaster Response		A7-A10, A13, A14, B3	all available data!	A7, A8, A13,	B3	all available data	A8-A10, A13, 14,	B3	all available data!	Less relevant		
Recovery, Reconst-ruction	A7-A10, A12, A13, 14, B1, B2, D2, D3	B3, C7, C8, C9, C10		A7, A13, D2, D3	A1, A5, A8, A12, B1, B2	B3	A7-A10, A12, A13, 14, B1, B2, D2, D3	B3, C7, C8, C9, C10		A1- 6, A8, A11	A9, A10, A12, A13, C7, C8, C9, C10	A14, B1, B2, B3, C1, C2
Prevention			see D4.3		B1, B2, B3	see D 4.3	8, B3	A1-A4, B1,B2, C1-C4, C7-C10			A1-A4, B1,B2, B3 C1-C4, C7-C10	see D 4.3
Prepared-ness	C7, C8, C9, C10			B2, C7, C8, C9, C10			A2-A4, B1, B2, C1, C2, C3, C4		EWS	A1, A3-A6,A10, A12, A13	A2, A4, A7, A8, A11, 14, B3, C7	B1, B2, C1, C2, C3, C4, C8, C9, C10, D2, D3

EWS=Early warning systems

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A11	Scherler, D., S. Leprince, and M. R. Strecker	2008	Glacier-surface velocities in alpine terrain from optical satellite imagery--Accuracy improvement and quality assessment, Remote Sensing of Environment, 112(10), 3806-3819, doi:10.1016/j.rse.2008.05.018
A11	Delacourt C., P. Allemand, E. Berthier, D. Raucoules, B. Casson, P. Grandjean, C. Pambrun, and E. Varel	2007	Remote-sensing techniques for analysing landslide kinematics: a review. Bulletin de la Societe Geologique de France 178 (2):89-100, doi: 10.2113/gssgfbull.178.2.89
A12	Tsutsui, K., S. Rokugawa, H. Nakagawa, S. Miyazaki, T. Chin-Tung Cheng Shiraishi, and S.-D. Yang	2007	Detection and Volume Estimation of Large-Scale Landslides Based on Elevation-Change Analysis Using DEMs Extracted From High-Resolution Satellite Stereo Imagery, IEEE Transactions on Geoscience and Remote Sensing Letters, 45(6), 1681 – 1696, doi: 10.1109/TGRS.2007.895209
A12	Martha, T. R., N. Kerle, V. Jetten, C. J. van Westen, and K. Vinod Kumar	2010	Landslide Volumetric Analysis Using Cartosat-1-Derived DEMs, Geoscience and Remote Sensing Letters, EEE, 7(3):, 582 – 586, doi: 10.1109/LGRS.2010.2041895
A13	Martha, T., N. Kerle, C. J. van Westen, and K. Kumar	2010	Characterising spectral, spatial and morphometric properties of landslides for semi-automatic detection using object-oriented methods, Geomorphology, 116(1-2): 24-36, doi: 10.1016/j.geomorph.2009.10.004
A13	Barlow, J., S. Franklin and Y. Martin	2006	High spatial resolution satellite imagery, DEM derivatives, and image segmentation for the detection of mass wasting processes, Photogrammetric Engineering and Remote Sensing, 72(6): 687-692.
A13	Stumpf, A. and N. Kerle	2011	Object-oriented mapping of landslides using Random Forests. Remote Sensing of Environment, 115(10):

			2564-2577, doi:10.1016/j.rse.2011.05.013
A14	Lu, P., A. Stumpf, N. Kerle, and N. Casagli	2011	Object-oriented change detection for landslide rapid mapping, IEEE Geoscience and Remote Sensing Letters, 99, 701-705, doi: 10.1109/LGRS.2010.2101045
A14	Park, N.-W. and K.-H. Chi	2008	Quantitative assessment of landslide susceptibility using high-resolution remote sensing data and a generalized additive model, Int. J. Remote Sens., 29(1), 247-264, doi: 10.1080/01431160701227661
B2, B3	Derron, M.-H. and M. Jaboyedoff	2010	Preface of the special issue LIDAR and DEM techniques for landslides monitoring and characterization"Nat. Hazards Earth Syst. Sci., 10, 1877–1879, doi:10.5194/nhess-10-1877-2010
B2, B3	Jaboyedoff, M., T. Oppikofer, A. Abellán, M.-H. Derron, A. Loye, R. Metzger, and A. Pedrazzini,	2010	Use of LIDAR in landslide investigations: a review: Natural Hazards, pp. 1-24, doi: 10.1007/s11069-010-9634-2
B2	Hiremagalur, J., K.S. Yen, K. Akin, T. Bui, T.A. Lasky and B. Ravani	2007	Creating Standards and specifications for the use of Laser Scanning in CalTrans projects. Technical report n° F/CA/RI/2006/46, California Department of Transportation, US, http://ahmct.ucdavis.edu/pdf/UCD-ARR-07-06-30-01-B.pdf
B1, B2, B3	Petrie, G. and C. K. Toth	2008	Introduction to laser ranging, profiling and scanning. In Topographic Laser Ranging and Scanning: principles and processing. Edited by: Shan, J., Toth, C. K., CRC Press, Taylor & Francis, 590p, ftp://ftp.ecn.purdue.edu/jshan/Zproject/proofs%20-%202nd%2020080922/01/51423_C001_Second_Pages_CT.pdf
B2	Travelletti, J., Delacourt, C., and J.-P. Malet	2011	Multi-date correlation of Terrestrial Laser Scanning, In: Stumpf, A., Malet, J.P. and N. Kerle (eds.) SafeLand deliverable 4.3. Creation and updating of landslide inventory maps, landslide deformation maps and hazard maps as input for QRA using remote-sensing technology. Edited for the SafeLand European project, Available at http://www.safeland-fp7.eu
B2, B3	Vosselman, G. and H. Maas	2010	Airborne and terrestrial laser scanning. CRC Press, Boca Raton, 318 pp.
B3	Van Den Eeckhaut, M., J. Poesen, G. Verstraeten, V. Vanacker, J. Nyssen, J. Moeyersons, L. P. H. v. Beek, and L. Vandekerckhove	2007	The use of LIDAR-derived images for mapping old landslides under forest. Earth surface processes and landforms 32, 754-769, doi: 10.1002/esp.1417
B3	Van Den Eeckhaut, M., J. Hervás, N. Kerle, and R. Supper	2011	Object oriented mapping of landslides under dense vegetation cover using LiDAR derivatives. In: Stumpf, A., Malet, J.P. and N. Kerle (eds.) SafeLand deliverable 4.3. Creation and updating of landslide inventory maps,

			landslide deformation maps and hazard maps as input for QRA using remote-sensing technology. Edited for the SafeLand European project, Available at http://www.safeland-fp7.eu
C1	Norland R.	2006	Differential Interferometric Radar for Mountain Rock Slide Hazard Monitoring. Technical Report, 4p. Available at Aaknes/Tafjord Beredskap IKS website www.aknes-tafjord.no
C2	Luzi, G., M. Pieraccini, D. Mecatti, L. Noferini, G. Guidi, F. Moia, and C. Atzeni	2004	Ground-based radar interferometry for landslides monitoring: atmospheric and instrumental decorrelation sources on experimental data. IEEE Trans. Geosci. Remote Sensing, 42(11), pp. 2454-2466, 10.1109/TGRS.2004.836792
C2	Pieraccini, M., G. Luzi, D. Mecatti, L. Noferini, and C. Atzeni	2006	Ground-based SAR for short and long term monitoring of unstable slopes. In: EuRAD European Radar Conference. European Radar Conference-EuRAD, 13-15 Sept Manchester, UK, pp. 92-95, doi: 10.1109/EURAD.2006.280281
C2, C3, C4	Rudolf, H., D. Leva, D. Tarchi, and A. J. Sieber	1999	A mobile and versatile SAR system. Proceedings of Geoscience and Remote Sensing Symposium, IGARSS 1999, 8 Jun - 02 Jul, Hamburg,Germany, pp. 592-594, doi: 10.1109/IGARSS.1999.773575
C3	Pipia L., X. Fabregas, A. Aguasca, C. Lopez-Martinez, J. J. Mallorqui, and O. Mora	2007	A subsidence monitoring project using a polarimetric GB-SAR sensor. Geoscience and Remote Sensing Symposium, 2007. IGARSS 2007, pp. 192-195, http://draco.icc.es/index.php/cat/content/download/3829/12792/file/a_subsidence_monitoring_project.pdf
C4	Antonello, G., N. Casagli, P. Farina, D. Leva, G. Nico, A. J. Sieber, and D. Tarchi	2004	Ground-based SAR interferometry for monitoring mass movements, Landslides, vol. 1, pp. 21-28, doi 10.1007/s10346-003-0009-6:
C4	Casagli N., F. Catani, C. Del Ventisette, and G. Luzi	2010	Monitoring, prediction, and early warning using ground-based radar interferometry. Landslides, doi:10.1007/s10346-010-0215-y
C4	Barla G., F. Antolini, M. Barla E. Mensi, and G. Piovano	2010	Monitoring of the Beauregard landslide (Aosta Valley, Italy) using advanced and conventional techniques, Engineering Geology,116(3-4): 218-235, doi:10.1016/j.enggeo.2010.09.004
C4	D'Aria, D., A. Ferretti, A.M. Guarnieri, and S.Tebaldini	2010	SAR Calibration Aided by Permanent Scatterers, IEEE Transactions on Geoscience and Remote Sensing, 48 (4): 2076 – 2086, doi: 10.1109/TGRS.2009.2033672
C5	Uratsuka, S.; T. Kobayashi, T. Umehara, T. Matsuoka, A. Nadai, M. Satake, and J. Uemoto	2010	Airborne SAR development at NICT: Concept for new Generation. International Archives of the Photogrammetry, Remote Sensing and Spatial Information Science, Volume XXXVIII, Part 8, Kyoto Japan. http://www.isprs.org/proceedings/XXXVIII/part8/headline/NICT%20special%20Session%20-%201/NTS11_20100608020300.pdf

C5	Prats, P., R. Scheiber, A. Reigber, C. Andres, and R. Horn	2009	Estimation of the Surface Velocity Field of the Aletsch Glacier Using Multibaseline Airborne SAR Interferometry, IEEE Transactions on Geoscience and Remote Sensing, 47(2): 419-430, doi: 10.1109/TGRS.2008.2004277
C6	M. Floris, C. Squarzoni, C. Hundseder, M. Mason and R. Genevois	2010	The use of IFSAR data in GIS-based landslide susceptibility evaluation, Geophysical Research Abstracts,Vol. 12, EGU2010-14777, EGU General Assembly 2010, http://meetingorganizer.copernicus.org/EGU2010/EGU2010-14777.pdf
C7	Delacourt, C., D. Raucoules, S. L. Mouélic, C. Carnec, D. Feurer, P. Allemand, and M. Cruche	2009	Observation of a large scale landslide in La Reunion Island using Differential SAR interferometry (JERS and Radarsat) and correlation of optical imagery (Spot 5), Sensors, 9 (1): 616-630, doi:10.3390/s90100616
C7	Werner, C., Wegmuller, U., Wiesmann, A. and T. Strozzi, T	2003	Interferometric Point Target Analysis with JERS-1 L-band SAR data. In: Proceedings IEEE IGARSS 7: 4359 – 4361, 21-25 July, Toulouse, France, doi: 10.1109/IGARSS.2003.1295515
C8	Oštir, K. & M. Komac, M.	2007	PSInSAR and DInSAR methodology comparison and their applicability in the field of surface deformations–A caseof NW Slovenia. GEOLOGIJA 50(1): 77–96, doi:10.5474/geologija.2007.007
C8, C9	Lauknes, T. R., A. Piyush Shanker, J. F. Dehls, H. A. Zebker, I. H. C. Henderson and Y. Larsen	2010	Detailed rockslide mapping in northern Norway with small baseline and persistent scatterer interferometric SAR time series methods, Remote Sensing of Environment, 114(9), 2097-2109, doi:10.1016/j.rse.2010.04.015
C8, C9, C10	Crosetto, M., O. Monserrat, R. Iglesias and B. Crippa	2010	Persistent Scatterer Interferometry: Potential, Limits and Initial C- and X-band Comparison, Photogrammetric Enginerring & Remote Sensing, 76 (9), 1061-1069
C8, C9, C10	Herrera, G., D. Notti, J. García-Davalillo, O. Mora, G. Cooksley, M. Sánchez, A. Arnaud, and M. Crosetto	2010	Analysis with C- and X-band satellite SAR data of the Portalet landslide area, Landslides, doi: 10.1007/s10346-010-0239-3 1-12.
C9	Cascini L., G. Fornaro and D. Peduto D.	2010	Advanced low- and full-resolution DInSAR map generation for slow-moving landslide analysis at different scales. Engineering Geology, 112 (1-4), 29-42, doi:10.1016/j.enggeo.2010.01.003
C9	Cascini L., G. Fornaro and D.	2009	Analysis at medium scale of low-resolution DInSAR data in slow-moving landslide-affected areas. ISPRS

	Peduto D.		Journal of Photogrammetry and Remote Sensing, 64(6), doi:10.1016/j.isprsjprs.2009.05.003
C9	Cascini L., S. Ferlisi, D. Peduto, G. Pisciotta, S. Di Nocera and G. Fornaro	2008	Multitemporal DInSAR data and damages to facilities as indicators for the activity of slow-moving landslides. In: Landslides and Engineered Slopes. From the Past to the Future. Chen Z., Zhang J., Li Z., Wu F., Ho K. (eds.). Proceeding of the 10th International Symposium on Landslides and Engineered Slopes, 30 June-4 July 2008, Xi'an, China, Taylor and Francis Group, London. Vol. II, pp. 1103-1109, doi: 10.1201/9780203885284-c145
C10	Costantini, M., S. Falco, F. Malvarosa, F. Minati and F. Trillo	2009	Method of persistent scatterer pairs (PSP) and high resolution SAR interferometry, IEEE Geoscience and Remote Sensing Symposium, III-904 - III-907 12-17 July 2009, Capetown, doi: 10.1109/IGARSS.2009.5417918,
C10	Nutricato, R., D. O. Nitti, F. Bovenga, F. Rana, C. D'Aprile, P. Frattini, G. Crosta, G. Venuti, M. T. Chiaradia, G. Ober, and L. Candela	2009	Morfeo Project: C- and X-Band SAR Interferometric Analysis over Alpine Regions (Italy). In: Fringe 2009 Workshop, Frascati, Italy, 30 November - 4 December 2009. ESA SP-677, http://earth.eo.esa.int/workshops/fringe09/proceedings/papers/s12_2nutr.pdf
General review	Michoud C., A. Abellán, M.-H. Derron and M. Jaboyedoff (Eds.)	2010	SafeLand deliverable 4.1: Review of Techniques for Landslide Detection, Fast Characterization, Rapid Mapping and Long-Term Monitoring. Available at http://www.safeland-fp7.eu
General review	Metternicht, G., Hurni, L., Gogu, R.	2005	Remote sensing of landslides: An analysis of the potential contribution to geo-spatial systems for hazard assessment in mountainous environments. Remote Sensing of Environment, 98(2-3): 284-303, doi:10.1016/j.rse.2005.08.004

General review	Kääb, A.	2000	Photogrammetry for early recognition of high mountain hazards: New techniques and applications, Physics and Chemistry of the Earth, Part B: Hydrology, Oceans and Atmosphere, Volume 25, Issue 9; Pages 765-770, ISSN 1464-1909, doi: 10.1016/S1464-1909(00)00099-X
General review	Kääb, A.	2008	Remote sensing of permafrost-related problems and hazards. Permafrost and Periglacial Processes 19 (2):107-136, doi: 10.1002/ppp.619
D1	Supper, R., I. Baroň, B. Jochum, A. Ita, K. Motschka, and E. Winkler	2010	Airborne Geophysics and Geoelectric and Inclinometric Monitoring at the Gschliefgraben Landslide, Berichte des Geologischen Bundesamtes, 82(Landslide Monitoring Technologies & Early Warning Systems), 50-57, http://www.geologie.ac.at/filestore/download/BR0082_050_A.pdf
D2	Hughes Clarke, J.E., L.A. Mayer and D.E. Wells	1996	Shallow-water imaging multibeam sonars: a new tool for investigating seafloor processes in the coastal zone and on the continental shelf. Marine Geophysical Researches, 18: 607–629, doi: 10.1007/BF00313877
D2	Mountjoy J. J., P. M. Barnes, and J. R. Pettinga JR	2009	Morphostructure and evolution of submarine canyons across an active margin: Cook Strait sector of the Hikurangi Margin, New Zealand. Marine Geology 260 (1-4):45-68. doi:10.1016/j.margeo.2009.01.006
D3	Martinez, J.F.	2010	3D Seismic Interpretation of Mass Transport Deposits: Implications for Basin Analysis and Geohazard Evaluation. In: D.C. Mosher et al. (eds.), Submarine Mass Movements and Their Consequences, Advances in Natural and Technological Hazards Research, Vol. 28, pp. 553-568. Springer Science + Business Media B.V., doi: 10.1007/978-90-481-3071-9_45

Annex 2: Overview of databases, software tools and institutions

Table 1: Passive optical sensors

Passive optical sensors	Photogrammetry and image correlation	Other image processing techniques
Databases	//eost.u-strasbg.fr/omiv/data_access.html	//eost.u-strasbg.fr/omiv/data_access.html
	//www.cage.curtin.edu.au/~gordonsj/isprs_wgv3/tests_datasets.html	//www.landcover.org
	//www-graphics.stanford.edu/data/3Dscanrep	//glovis.usgs.gov
	http://earth.esa.int/EOLi/EOLi.html	http://earth.esa.int/EOLi/EOLi.html
	//edcsns17.cr.usgs.gov/NewEarthExplorer	//edcsns17.cr.usgs.gov/NewEarthExplorer
	//gdsc.nlr.nl/FlexCatalog/catalog.html#	//gdsc.nlr.nl/FlexCatalog/catalog.html#
		//www.eoportal.org
		//www.euspaceimaging.com
		//www.eurimage.com

Table 1: Passive optical sensors, continued

Passive optical sensors	Photogrammetry and image correlation	Other image processing techniques
Commercial software	Leica Photogrammetric Suite //www.erdas.com/products/LPS/LPS/Details.aspx	Erdas Imagine //www.erdas.com/products/ERDASIMAGINE/ERDASIMAGINE/Details.aspx
	PhotoModeller //www.photomodeler.com	eCognition //www.ecognition.com
	SAT-PP //www.photogrammetry.ethz.ch/research/satpp/index.html	
		ENVI 4.8 //www.ittvis.com/language/en-us/productsservices/envi.aspx
		ENVI-EX //www.ittvis.com/ProductsServices/ENVI/ENVIEX.aspx
Free software	COSI Corr //www.tectonics.caltech.edu/slip_history/spot_coseis/download_software.html	InterImage //www.lvc.ele.puc-rio.br/projects/interimage
	MicMac //www.micmac.ign.fr	ILWIS //www.itc.nl/Pub/Home/Research/Research_output/ILWIS_-_Remote_Sensing_and_GIS_software.html
		Fiji //pacific.mpi-cbg.de/wiki/index.php/Fiji
		Orfeo Toolbox //www.orfeo-toolbox.org/otb

Table 1: Passive optical sensors, continued

Passive optical sensors	Photogrammetry and image correlation	Other image processing techniques
		Plugins for eCognition and IDL //tu-freiberg.de/fakult3/mage/geomonitoring/software/software.html
		EBImage for R //www.bioconductor.org/packages/2.2/bioc/html/EBImage.html
Points of contacts, institutions, companies	//www.geoimaging.tugraz.at	//www.itc.nl/OOA-group
	//www.fh-oow.de/institute/iapg/	//www.zgis.at/research/
	//www.intergraph.com/global/de/photo/gdp.aspx	//www.ecognition.com/community
	//www.photogrammetry.ethz.ch	//www.un-spider.org/
	//www.ifp.uni-stuttgart.de/	//www.disasterscharter.org/home
	//grail.cs.washington.edu/software-data/	//tu-freiberg.de/fakult3/mage/geomonitoring/

Table 2: Active optical sensors

Active optical sensors	Ground - based	Airborne
Databases		http://en.wikipedia.org/wiki/National_LIDAR_Dataset
		http://www.grassbook.org/data_menu2nd.php
Commercial software	Polyworks //www.innovmetric.com	Scop++ http://www.inpho.de/index.php?seite=index_scope
	RiScan Pro //www.riegl.com/products/software-packages/riscan-pro/	
	Leica Cyclone //www.leica-geosystems.com/de/Leica-Cyclone_6515.htm	
Free software	CloudCompare http://www.danielgm.net/cc/	
	UVACAD //157.88.193.21/~uvacad/	
	Full Analyze //fullanalyze.sourceforge.net	Full Analyze //fullanalyze.sourceforge.net
Points of contacts, institutions, companies	Surveyors (Optech, Riegl, Leica, Trimble, MDL)	Surveyors (Leica, Optech, Riegl, IGI, Toposys)
	Universities (Lausanne, Durham, ETH, Calgary, Vienna, Curtin, Barcelona, Padova, etc).	
	Research Centers (USGS, ITC Neetherlands, NGI+NGU Norway, NRC Canada, INGV, Italy, IG Spain)	
	//isprsv6.lboro.ac.uk	
	//www.iaeg.info/Commissions/C193Dterrestriallaserscanningtechnology/tabid/82/Default.aspx	

Table 3: Active microwave sensors

Active microwave sensors	Ground-based	Airborne	Satellite
Databases		//www.intermap.com/nextmapeurope	//eopi.esa.int/esa/esa
		//earth.eo.esa.int/polsarpro/input.html	//gdsc.nlr.nl/gdsc
Commercial software	IBIS DV //???		SARScape //www.ittvis.com/ProductServices/ENVI/SARscape.aspx
	GRAPeS //???		GSAR //???
	LiSA Mobile DV //???		Diapason //www.altamira-information.com
Free software		PolSARpro //earth.eo.esa.int/polsarpro/input.html	Efidir //efidir-www.ampere.inpg.fr
			ROI PAC //www.roipac.org
			STAMPS //radar.tudelft.nl/~ahooper/stamps
Points of contacts, institutions, companies	Joint Research Centre //ec.europa.eu/dgs/jrc/index.cfm	//www.intermap.com/nextmapeurope	Gamma remote sensing //www.gamma-rs.ch
	LiSALAB-Ellegi //www.lisalab.com/home	//earth.eo.esa.int/polsarpro/input.html	Northern Research Institute //www.norut.no/en/Norut
	Ingegneria Dei Sistemi //www.idscompany.it		Altamira //www.altamira-information.com
	Aresys //www.aresys.it		TRE //www.treuropa.com

Table 3: Active microwave sensors, continued

Active microwave sensors	Ground-based	Airborne	Satellite
	Gamma Remote Sensing //www.gamma-rs.ch		

Table 4: Offshore methods

Others	Offshore vessel and platforms
Databases	**???**
Commercial software	Geo Swath Plus //www.km.kongsberg.com/ks/web/nokbg0240.nsf/AllWeb/DA313E43C77A125AC12574BF003439F8?OpenDocument
	SMT Kingdom Suite //www.seismicmicro.com/
	Petrel //www.slb.com/services/software/geo/petrel.aspx
Free software	**???**
Points of contacts, institutions, companies	**???**

Table 5: National landslide inventories

Country	Database
Andorra	Andorran Research Inst. (IAE) http://www.cenma.ad/mbaseriscos.htm
Andorra	Andorran Government http://www.ideandorra.ad/geoportal/framesetup.asp
Austria	Geological Survey of Austria http://geomap.geolba.ac.at/MASS/index.cfm
Czech Republic	Czech Geological Survey http://www.geology.cz/app/dbsesuvy (intranet; no public access)
France	French Geological Survey (BRGM) http://www.bdmvt.net
Greece	Inst of Geology and Mineral Exploration (IGME) http://maps.igme.gr/website_ext/igme_master_ext/viewer.htm
Ireland	Geological Survey of Ireland http://www.gsi.ie/mapping.htm
Italy	Inst for Environmental Protection and Research (ISPRA) http://www.sinanet.apat.it/progettoiffi
Norway	Geological Survey of Norway (NGU) www.skrednett.no

Table 5: National landslide inventories

Country	Database
Sweden	Swedish Civil Contingencies Agency http://ndb.msb.se/
United Kingdom	British Geological Survey http://www.bgs.ac.uk/landslides/ (only information on database)