

Chapter 2

Innovative Techniques for the Detection and Characterization of the Kinematics of Slow-Moving Landslides

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Abstract Remote sensing has been proven useful for landslide studies. However, conventional remote sensing techniques based on aerial photographs and optical imageries seem to be more suitable for detecting and characterizing rapid-moving landslides. This section introduces several innovative remote sensing techniques aiming at the characterization of the kinematics (e.g. displacement pattern, deformation, strain) of slow- to moderate-moving landslides. These methods include Persistent Scatterers Interferometry (PSI), automatic surveying using total station integrated with GPS, Ground-Based Synthetic Aperture Radar Interferometry (GB-InSAR), image correlation of catalogues of optical photographs (TOP) and Terrestrial Laser Scanner (TLS) point clouds. Three case studies, including the Arno river basin (Italy), the Valoria landslide (Italy) and the Super-Sauze landslide (France) are presented in order to highlight the usefulness of these techniques.

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Abbreviations

ALS	Airborne Laser Scanner
CPT	Coherent Pixels Technique
DInSAR	Differential InSAR
EW	Early Warning
GB-InSAR	Ground-based Synthetic Aperture Radar Interferometry
IPTA	Interferometric Point Target Analysis
LOS	Line-of-Sight
PS	Persistent Scatterers
PSI	Persistent Scatterers Interferometry
InSAR	SAR Interferometry
SBAS	Small Baseline Subset
SPN	Stable Point Network
StaMPS	Stanford Method for Persistent Scatterers
TLS	Terrestrial Laser Scanner
TOP	Terrestrial Optical Photogrammetry
DEM	Digital Elevation Model
GPS	Global Positioning System

2.1 Introduction

Data products of remote observing systems are increasingly available with higher spatial and temporal resolution and offer new opportunities for the detection, mapping, characterization and monitoring 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.

The choice of an adequate observing system depends on the landslide type and size, the range of observed velocity, the required frequency of acquisition, the desired accuracy and the financial constraints. Displacement monitoring techniques applied on landslides can be broadly subdivided in two main groups: geodetic and remote-sensing techniques.

- Geodetic surveying techniques consist in detecting geometrical changes in the landslide topography by measuring geometric parameters such as angles, distances or differences in elevation (levelling, tacheometry; Naterop and Yeatman 1995). These techniques necessitate the installation of targets in and outside the landslide and in measuring their position at different times. They have the advantage to be very accurate (0.2–2.0 cm) with a high potential of automation (Malet et al. 2002; Jaboyedoff et al. 2004; Foppe et al. 2006). Furthermore, many authors demonstrated the efficiency of permanent (Malet et al. 2002) and non-permanent (Squarzoni et al. 2005; Brunner et al. 2007) differential Global

Positioning System (dGPS) for landslide monitoring with a centimetric accuracy during any daytime and weather conditions. However, because landslides can show highly variable displacement rates in time and space according to the local slope conditions (bedrock geometry, distribution of pore water pressures), the major drawbacks of the geodetic techniques are (1) to provide only discrete point measurements of the displacement and (2) the costs of installation and maintenance of the survey network. They are usually only justified in the case of a real risk for the population.

- Remote sensing surveying techniques are interesting tools to obtain spatially-distributed information on the kinematics (Delacourt et al. 2007) and can be operational from spaceborne, airborne and ground-based platforms. Remote-sensing techniques give the possibility to discriminate stable and unstable areas and to map sectors within the landslide with different kinematics from a regional to a local scale. They are also useful tools for a process-based analysis of the deformation field affecting the slope (Casson et al. 2005; Teza et al. 2008; Oppikofer et al. 2008). In the last decades, the development of ground-based platforms for landslide monitoring at the local scale provided many advantages over spaceborne and airborne platforms despite a shorter spatial coverage (Corsini et al. 2006). The geometry and frequency of acquisitions are more flexible and adaptable to any type of local environment. In addition permanent installations of ground-based platforms allow continuous monitoring (Casagli et al. 2004; Delacourt et al. 2007). Three main categories of ground-based remote sensing techniques are used in landslide monitoring: Ground-Based Synthetic Aperture Radar Interferometry (GB-InSAR), Terrestrial Laser Scanner (TLS) and Terrestrial Optical Photogrammetry (TOP).

In this section, several of the above mentioned innovative remote sensing techniques are introduced and their usefulness in the detection and characterization of the kinematics (e.g. displacement pattern, deformation, strain) of slow- to moderate-moving landslides is highlighted through three case studies.

2.2 Detection and Characterization of Slow-Moving Landslides from Persistent Scatterers Interferometry (PSI)

2.2.1 *The Principle of Persistent Scatterers Interferometry (PSI)*

For studies of slow-moving landslides, SAR interferometry (InSAR), which uses the phase content of radar signals for estimating surface deformation, regardless of weather and night condition, has recently already become a widely-used technique (Gens and Van Genderen 1996). In particular, satellite InSAR represents a typical example of repeat-pass interferometry, combining two or more SAR images of

similar scene of terrain from slightly displaced passes of SAR sensor at different times (Massonnet and Feigl 1998). Besides, side-looking imaging radar ensures improvement of pixel resolution in viewing direction. Traditional satellite InSAR technique is mainly focusing on differential InSAR (DInSAR) approach which primarily employs two corresponding interferograms for differential measurements (Massonnet and Feigl 1998; Rosen et al. 2000). DInSAR was proven useful in studies of slow-moving landslides (e.g. Fruneau et al. 1996; Singhroy et al. 1998; Xia et al. 2004; Strozzi et al. 2005). It largely fills the gap of conventional remote sensing techniques of aerial photos and optical images, which are chiefly used for mapping rapid-moving shallow landslides and debris flows (Lu et al. 2011).

However, the conventional DInSAR approach, which is based on the assumption that surface deformation change is linear, is often affected by temporal decorrelation and atmospheric disturbances (Massonnet and Feigl 1998; Ferretti et al. 2001). These disturbing factors, which produce a significant bias during the phase measurement and the difficulty in fulfilling baseline criteria, bring the need for further advanced processing of SAR images. One possible solution is to include multi-temporal SAR images for a long-term interferogram processing, known as the technique of Persistent Scatterers Interferometry (PSI). Over recent years, several PSI approaches have been developed for the purpose of extracting long-term stable radar benchmarks, namely Persistent Scatterers (PS), from some multi-interferogram analysis of SAR data based on different statistical approaches.

For instance, a PSInSARTM technique was firstly developed by Ferretti et al. (2001) and then improved by Colesanti et al. (2003). Another approach, known as Stanford Method for Persistent Scatterers (StaMPS), which calculates a time series of deformation with spatially-correlated nature of ground deformation, was initially developed by Hooper et al. (2004) and further modified by Hooper et al. (2007) for improvement of measuring accuracy. Besides, the approach of Interferometric Point Target Analysis (IPTA), which detects persistent benchmarks in low-coherence regions and includes large baselines for phase interpretation, was suggested by Werner et al. (2003) and Strozzi et al. (2006). In addition, two small baseline approaches were developed, including the Coherent Pixels Technique (CPT) proposed by Mora et al. (2003) and Blanco-Sanchez et al. (2008), and Small Baseline Subset (SBAS) indicated by Berardino et al. (2002), Casu et al. (2006) and Lanari et al. (2004). Similarly, a stable point network (SPN) mode was also reported by Crosetto et al. (2010) and Duro et al. (2003). These approaches mentioned above enable a measurement of ground motion with millimeter accuracy (Lu et al. 2010).

2.2.2 Detection and Characterization of Slow-Moving Landslides from PSI at Catchment Scale

Due to its large spatial coverage, PSI technique can be useful in detecting landslide at regional scale. In this section, a case study for detecting and characterizing slow-moving landslides at catchment scale is illustrated on the Arno river basin (central

Italy). The whole basin covers about 9,130 km² with 78 % (7,190 km²) area across the mountainous and hilly areas. Previous researches have mapped more than 27,000 landslides within the whole basin, most of which are slow-moving deep-seated landslides (Catani et al. 2005; Farina et al. 2006).

The PS data were processed from the technique of PSInSARTM (Ferretti et al. 2001) by Tele-Rilevamento Europa (TRE) on behalf of the Arno River Basin Authority. In total 102 RADARSAT-1 images with incidence angle of 30°–37°, covering the period from 2003 to 2006 with the acquisition interval of 24 days, were analyzed. Among these images, 54 of them are ascending data and 48 of them are descending data. More than 700,000 PS were finally derived with a pre-defined coherence threshold above 0.60. The precision of displacement rates is ranging between 0.1 and 2.0 mm·year⁻¹ along Line-of-Sight (LOS). The geocoding accuracy is within 10 m in east–west and 5 m in the north–south direction.

Lu et al. (2012) proposed a semi-automatic approach for detecting slow-moving landslides. At its initial stage, a flat mask was used on PS data in order to focus on PS exclusively located in the mountainous and hilly areas. Then two statistical approaches were applied in the following analyses: (1) the Getis-Ord G_i^* Statistics (Getis and Ord 1996) and (2) the kernel density estimation (Silverman 1986). The G_i^* statistics (Getis and Ord 1996) was mainly employed to estimate the clustering level of PS data. It specified a single PS at a site i , and its neighbours j within a searching distance d . For each single PS at a site i , the G_i^* index was calculated as:

$$G_i^*(d) = \frac{\sum x_j + x_i - n_{ij} \bar{x}}{s^* \{[(n \cdot n_{ij}) - n_{ij}^2] / (n - 1)\}^{0.5}} \quad (2.1)$$

where n is the number of calculated PS datasets. n_{ij} is the number of PS within the searching distance d , which is actually the sum of PS at the site i and its neighbours j . x is the velocity of each single PS. s^* is the standard deviation of PS velocity for the entire dataset. The searching distance d was defined as 114 m, calculated by the average distance of the shortest path to a channel and the shortest distance to a ridge pixel calculated based on steepest descent direction as proposed by Tucker et al. (2005).

The kernel density estimation was then used to fit a smoothly tapered surface as a hotspot using a kernel estimator defined as

$$f(x) = \frac{1}{nh} \sum_{i=1}^n K\left(\frac{x - X_i}{h}\right) \quad (2.2)$$

where h is the searching window width, $x - X_i$ is the distance of each calculating pixel to each PS i . K is the quadratic kernel function defined as:

$$\begin{aligned} K(x) &= \frac{3}{4}(1 - x^2), |x| \leq 1 \\ K(x) &= 0, x > 1 \end{aligned} \quad (2.3)$$

This kernel estimator was calculated on all PS datasets, with the corresponding G_i^* index as the weighting factor. The final output was a smooth kernel density map that represents PS hotspots for an easier and straightforward visualization for landslide detection.

Figure 2.1 is the derived hotspot map reported by Lu et al. (2012), indicating where potential slow-moving landslides might exist. It covers part of the Arno river basin of Pistoia-Prato-Firenze and the Mugello areas. Hotspots with high positive kernel density values are displayed with blue color whereas hotspots with low negative values are given in red color. These blue and red hotspots reveal those areas which are potentially affected by slow-moving landslides within the detection precision of PSI technique. The deeper the color is, the more intense high-velocity PS datasets are clustered, thus suggesting the presence of high density of mass movements. The color of hotspots renders the information of moving direction. Clustering of PS moving towards LOS (positive velocity) is represented by blue hotspot whereas clustering of PS moving away from LOS (negative velocity) is rendered in red hotspot. In addition, the radius of each hotspot suggests the extent of a potential landslide-affected area.

2.3 Ground-Based Multi-instruments Monitoring of Slow- to Moderate-Moving Landslides

2.3.1 The Combination of Geodetic and Remote Sensing Techniques for Monitoring at the Slope Scale

In the case of reactivation of slow- to moderate-moving landslides, the mechanism of failure and evolution at the slope scale is governed by a combination of different processes. Continuous monitoring systems were used for uncovering such complex movement patterns (Malet et al. 2002; Petley et al. 2005a). For such studies, the critical components to assess landslide hazard are efficient information on the velocity and acceleration of the moving masses (Hervás and Bobrowsky 2009). In some cases, early-warning based on real-time continuous monitoring is in principle possible by exploiting empirical relationships linking the progressive acceleration to the timing of failure (Petley 2004; Petley et al. 2005b).

In order to compare the performance of real-time continuous geodetic (automated total station measurements) and ground-based remote sensing techniques (GB-InSAR measurements), a field test was carried out from 23 to 25 February 2009 at the Valoria landslide (Northern Apennines). The particular focus was to document the spatial and temporal patterns of slope movements during reactivations and to compare the instrument's pros and cons in the perspective of surveying and early warning.

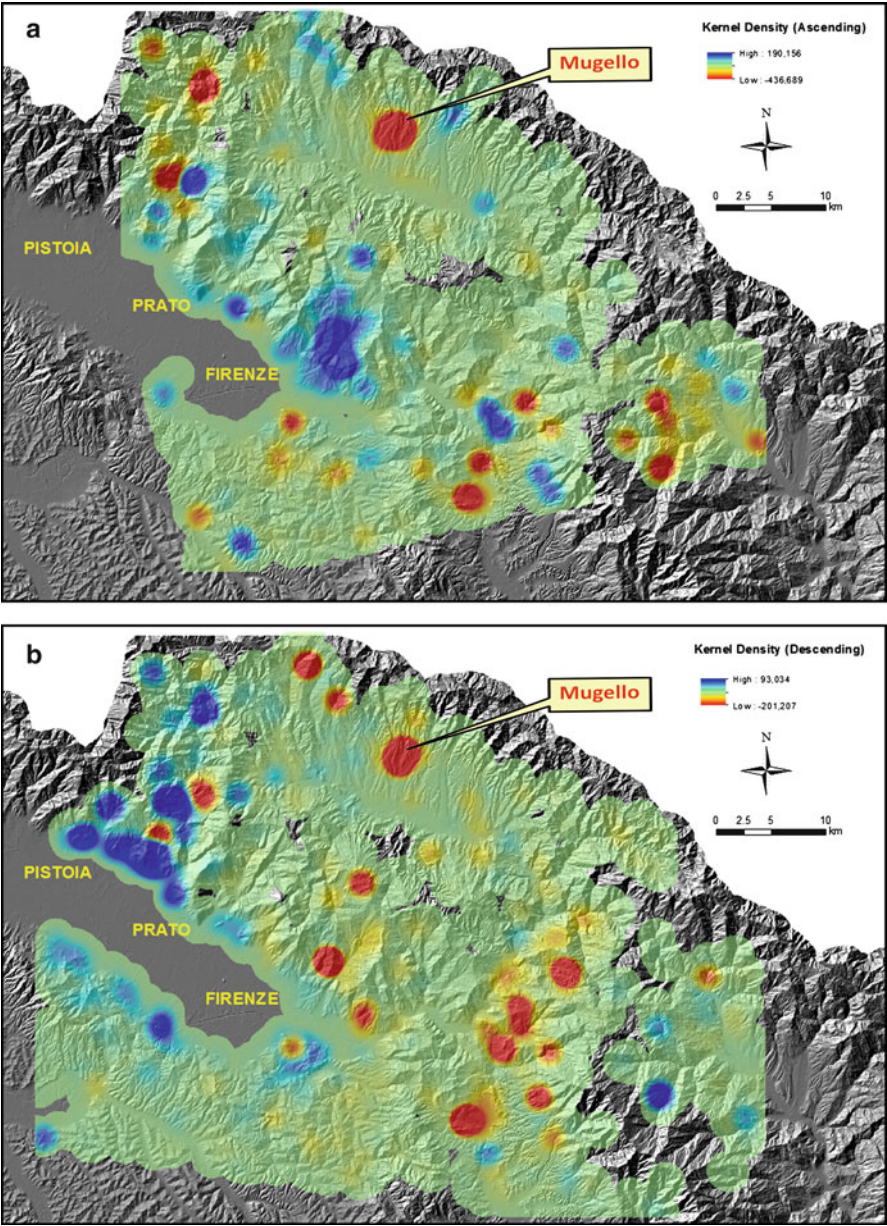


Fig. 2.1 The landslide hotspot map of Pistoia-Prato-Firenze and Mugello basin (central Italy), generated from: (a) ascending RADARSAT PSI; (b) descending RADARSAT PSI (Lu et al. 2012)

The landslide is a complex and composite mass movement. Rotational and translational slides in the source area and subsequent earthflows in the track and accumulation zones are associated (Fig. 2.2). The landslide activity since 2001 ranges from persistent slow movements, associated with relatively low hazard and risk levels, to phases of accelerated movements in the scale of some $\text{m}\cdot\text{h}^{-1}$ to $\text{m}\cdot\text{day}^{-1}$ (Ronchetti et al. 2007; Corsini et al. 2009).

A continuous topographic monitoring system, based on a Leica TCA2003 automated total station is operated since March 2008. The system was installed in response to the repeated reactivations that affected the landslide since 2001 and it was designed to cover the whole landslide from the main upper scarp to the toe. The monitored area extends over more than 3 km in length and ranges from altitudes between 1,390 and 520 m. The automated total station is located midway in the slope, on a panoramic position located a few hundred meters northeast of the landslide (Fig. 2.2). More than 40 prisms were placed inside the landslide and 6 prisms were placed in stable areas as reference points for measurements correction. The hardware setup includes a control unit (industrial computer) that is also used for a permanent GPS network which was installed nearby the topographic survey station (Fig. 2.3 I–III). The technical characteristics of the system (total station and GPS) are summarized in Table 2.1.

The total station is mounted on a tribrach on top of a reinforced concrete pillar that is anchored 1 m into the ground. The instrument is protected from environmental impacts through a ventilated case made of 5 mm thick glass (Fig. 2.3 I, II). This hardware solution was set to perform a measuring cycle in a 3 h duty schedule. During movement, prisms are followed by the total station using the instrument's Automatic Target Recognition functionalities. The search window was set to 10 m, so that the system is potentially capable of measuring velocities up to $3\text{ m}\cdot\text{h}^{-1}$ assuming the prism remains visible to the laser beam. Daily and seasonal climatic conditions produce variations in distance measurements that are corrected by applying p.p.m. corrections and using the reference prisms installed outside of the landslide body as fixed locations.

From 23 to 25 February 2009, during a complete reactivation event, a ground-based synthetic aperture radar interferometry (GB-InSAR) test was carried out. For this purpose, an IBIS-L device, manufactured by IDS (Ingegneria dei Sistemi, Pisa, Italy) was used (Fig. 2.4).

GB-InSAR was tested to assess if it can be used to complement measurements obtained by the total station for movement rates up to cm to $\text{m}\cdot\text{day}^{-1}$. The high water content in the landslide mass during the reactivation is particularly challenging for GB-InSAR since phase ambiguity and loss of coherence due to ground moisture changes data processing (Tarchi et al. 2003; Antonello et al. 2004; Corsini et al. 2006). To cover the entire slope, the radar was first directed toward the upper slope for 17 h, and then toward the lower slope for 24 h (Fig. 2.2). In order to have the possibility to compare results between radar and total station, new topographic prisms were installed in the moving deposits within the radar scene coverage.

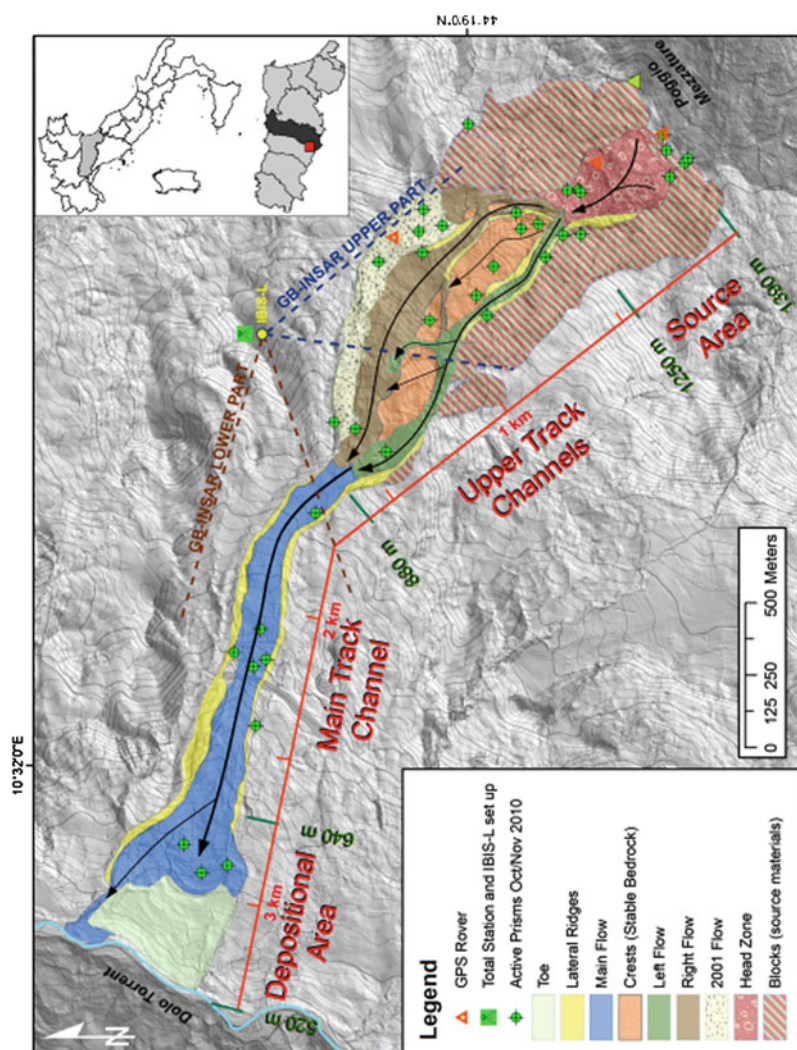


Fig. 2.2 The Valoria landslide (Northern Apennines, Italy). Slope deformations are characterized by earthflows developing in the source area and transporting materials around two stable crests downslope. The locations of prisms targets automatically surveyed by a total station since March 2008 along with GPS rover stations are marked. The site monitoring is complemented by two InSAR surveys conducted in February 2009 and targeting the upper and lower landslide body, respectively

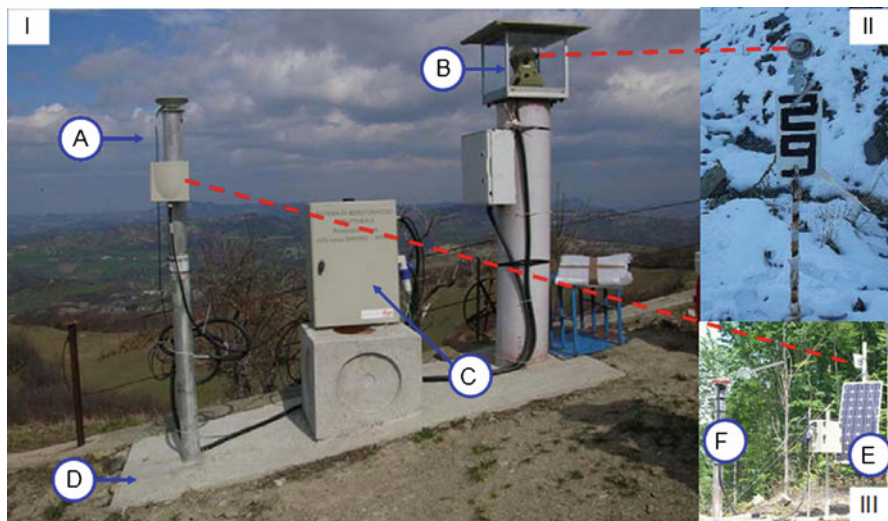


Fig. 2.3 Automated topographic monitoring station with integrated GPS system. **I.** (A) GPS Master and WLAN Antenna, (B) Automated total station, (C) Controller unit with OEM computer, power supply and modem for data transmission, (D) Foundation with GPS and total station monuments; **II.** Optical prism installed inside the landslide, target acquisition via laser beam; **III.** Rover GPS installed inside landslide materials: (E) Autonomous power supply through solar panel with controller and backup battery, WLAN streaming data transmission, (F) GPS Antenna mounted on GPS monument

The IBIS-L consists of “Stepped Frequency Continuous Wave” radar unit (Fig. 2.4). The main features of the device can be found in Table 2.2, while specific operational parameters for the two surveys conducted at the Valoria landslide are summarized in Table 2.3. The IDS developed software (GRAPeS) was used to process data. A calibration dataset was created using about 30 raw images and a coherence threshold of 0.6. This calibration set includes pixels that are above the coherence threshold in all the 30 scenes. Displacement is then calculated for each coherent pixel by stacking all the collected scenes, computing phase differences between subsequent scenes and using stable areas as proxies for estimating atmospheric correction. The results can be visualized as raster maps of displacement or velocity, or as time series for each single coherent pixel.

2.3.2 Comparison of the Monitoring Datasets

The evaluated Leica robotic total station and IBIS-LGB-InSAR systems performed well in detecting movements covering almost the entire case study site (Fig. 2.5). While highly LOS velocities of few $\text{mm}\cdot\text{h}^{-1}$ were noted for both techniques the surveyed prisms generally contained a higher level of noise for slow movements

Table 2.1 Main parameters of the automated total station set-up with integrated GPS system

	Instrument parameter	Description
Total Station	Type	1 Leica TCA 2003 (Leica Geosystems 2004)
	Operating distance	<2,000 m
	Survey mode	Automatic target recognition ATR, custom defined intervals, <i>e.g.</i> 3 h
	Total station position control	Bi-directional Leica Nivel 210 (mrad, temperature, sampling 300 ms)
	Angular standard deviation	0.01 mgon
	Distance standard deviation	1 mm + 1 ppm/3.0 s
	Survey targets	41 prisms: 35 inside and 6 for control
	External communication	GSM modem/satellite link
GPS	Master station	1 Leica GMX902 GG (L1,L2) dual frequency receiver, antenna Leica AX1202GG, grid connected (220 V) with back-up battery
	Rover	3 receivers Leica GMX901 GG (L1, 12 CH.,1Hz), autonomous power supply (solar panel + battery)
	Data transmission link	Continuous data streaming via GMX902 WLAN modena
Master unit	Operating system	Windows XP
	Total station/GPS integration	Software based, direct link to monitoring equipment and data storage
	Power supply	220 V grid-tied with 12 V battery as backup power
	Remote data transmission	GPRS modem

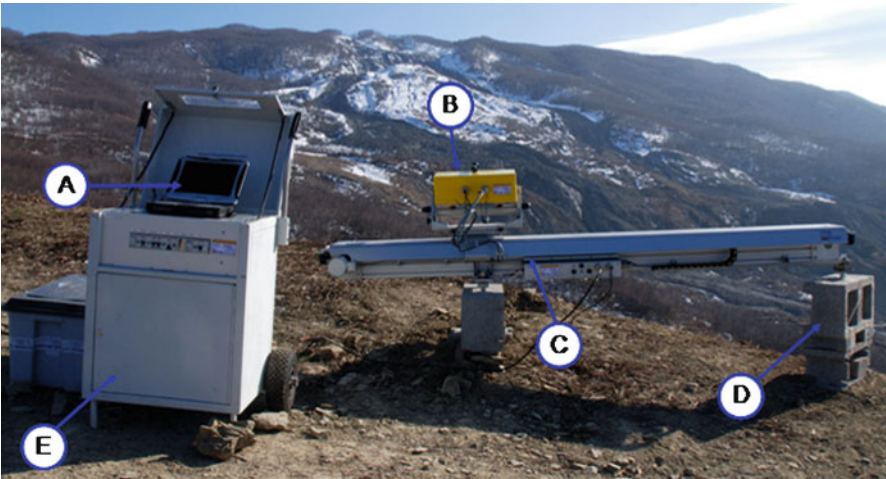


Fig. 2.4 GB-InSAR survey of the upper part of the Valoria landslide. Set-up: (A) Control unit (Mobile PC with software), (B) Radar sensor head, (C) Linear scanner (2.5 m rail with sled), (D) Support system (temporary or permanent mounts allowing for repeated observations), (E) Power module (controller, fuses, 12 V batteries connected in serial)

Table 2.2 GB-InSAR technical characteristics (IDS, IBIS-L model)

Instrument parameter	Description
Frequency	Ku band (available also in X band)
Radar type	Stepped Freq. Cont. Wave (SF-CW)
Operative range	[10–4,000] m
Range resolution	0.75 (0.5) m
Cross-range resolution	4.38 mrad
Displ. accuracy	up to 0.1 mm
Acquisition time	≥ 5 min
Phase ambiguity limit	~ 4.4 mm
Installation time	~ 2 h
Power supply	24 VDC or electrical network
Size	$250 \times 100 \times 100$ cm
Weight	~ 200 kg
Power consumption	70 W

Table 2.3 Operational parameters of the IBIS-L ground-based InSAR surveys conducted at the Valoria landslide

	Upper part	Lower part
Date	25/02/2009	24/02/2009
Distance to hillslope [m]	300–1,900	450–1,300
Horizontal antenna aperture [degree]	38	38
Range resolution [m]	0.5	0.5
Cross-range resolution [mrad]	4.5	4.5
Acquisitions per hour [–]	8	9
Duration [h]	17	24

(Fig. 2.5; Prisms 42, 44). The observed higher noise levels in the observations of slow moving events are due to the lower limit of detection of the total station. Maximum velocity values measured in the upper part at the right flow by the GB-InSAR reached about 99 mm over a period of 17 h and about 336 mm over 24 h in the central part of the main flow. Thus, an average maximum LOS velocity of about $5.8 \text{ mm}\cdot\text{h}^{-1}$ was measured in the upper and about $14 \text{ mm}\cdot\text{h}^{-1}$ in the lower part. Higher velocities in the lower part were evidenced by prisms surveyed by the total station with maximum rates of $52 \text{ mm}\cdot\text{h}^{-1}$ (Prism 28a) and $10.7 \text{ mm}\cdot\text{h}^{-1}$ (Prism 51). Further, the data acquisition for the entire field-of-view at once allows for apparent distinction of zones of high and low displacements on qualitative scales using GB-InSAR while topographic surveys are restricted to few discrete observations. However, flow movements can be variable within just a few meters yielding better absolute measurements when using prisms targets compared to GB-InSAR measurements without corner reflectors. It should be noted from the plots in Figure 2.5 that closer LOS of InSAR to the slope movement direction produces a better fit between InSAR displacement and “real” displacement measured by prisms (Prism 28a).

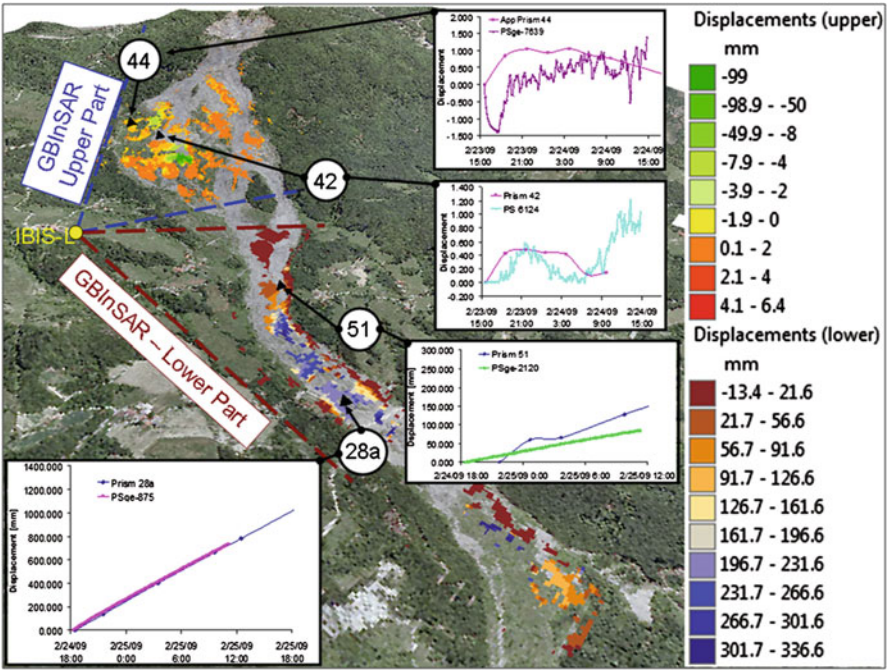


Fig. 2.5 Results of displacement monitoring at the Valoria landslide during the winter 2009 reactivation. Prisms were measured by an automated total station from nearby the position of the IBIS-L ground-based InSAR. Using an IBIS-L terrestrial Radar instrument, surveys of the *upper* and *lower* landslide body were obtained. The displacements shown are in the Line-of-sight (LOS) direction with respect to the location of the instrument reaching maximum values of about 336 mm over 24 h of observation

Both adopted monitoring systems can be compared on the basis of general knowledge, as well as on the basis of the information gathered during the field tests. The assessment of several relevant issues for each system is summarized in Table 2.4. During the set-up phase of topographic and ground-based InSAR monitoring surveys, field and installation logistics are crucial. For both instruments, operational cost during the initial phase of landslides monitoring are high due to the unit and site development costs. Therefore, view shed, distance, incidence angle between line-of-sight and slope displacement vector, power supply, accessibility, and instrument safety need to be factored in to ensure a successful survey. Where highly precise measurements are necessary due to slow movements (mm-month^{-1}), both the total station and the IBIS-L instrument require a stable and firm foundation. As regards spatial coverage, the evaluated Leica robotic total station system has an angle of operation of 360° covering almost the entire case study site with some line-of-site restrictions. Although line-of-sight restrictions also affect GB-InSAR, in good coherence conditions, spatially distributed and continuous information can be obtained for one LOS direction at a time. In practice this means that for the

Table 2.4 The comparison between the total station and the GB-InSAR for the Valoria landslide monitoring

Evaluation criteria	Total station with integrated GPS	GB-InSAR
Unit cost	Approx. 40.000 €	Approx. 150.000 €
Initial installation and setup	1 week, min. 1 m ² of property with good line of sight coverage (elevated point)	2–3 h, portable unit requires min two persons for set up and transport
Autonomous operation mode	Yes, requires 220 V power supply (alternatively with solar panels)	Yes, requires 220 V power supply (alternatively with solar panels)
Spatial coverage (extent and resolution)	Point targets (optical prisms), max observation distance 2 km, line of site contact necessary but 360° angle of operation	Up to 4 km range distances. Movements are pixel-averaged for the entire field of illumination, Spatial resolution decreases with increasing distance. Operational on a 60° view
Temporal resolution	Near-real-time (a cycle of 40 prisms takes about 20 min to complete)	Near-Real-time observations (scene every 6–10 min depending on the max range distance) independent of dormant or active state of landslide
Displacement resolution	mm (ang. St.dev. 0.01 mgon, dist. st. dev 1 mm + 1 ppm)	mm to sub-mm
Displacement range	mm to max range distance. However, stability of targets makes it so that in Valoria we managed to measure max up to 120 m before losing the point	Theoretically limited only by maximum distance of operation (4 km). However, the “real object” captured in the pixel may change in time
Velocity range	Up to m/h. However, loss of prims is likely in a few days if velocities exceed m/h → active state	4.4 mm/10 min. Maximum detection range limited by wavelength
Remote data accessibility	Yes, if using a router/modem to connect to the on-site PC	Yes, if using a router/modem to connect to the on-site PC
Data processing	On-site, windows based OEM PC, on-site post processing possible	On-site, windows based laptop PC, on-site post processing possible
Maintenance	Frequent visits prism targets necessary when landslide is active to replace or reorient the prisms (2 operators needed: 1 at the total station and 1 in the field)	After installation no maintenance necessary, visits only for retrieval of data
Reliability	High, after initial phase, autonomous operation continues for more than 3 years. Minor interruptions only in remote data transmission. Maintenance at prism targets to ensure line-of-sight contact with survey station	To be tested in the long term
Early warning capability	Yes, transmission of automated warning messages possible based on “rules” that account for displacement and/or velocity of individual prisms or group of prisms	Yes, transmission of automated warning messages possible based on max velocity in the scene

total station the number of prisms determines the availability of displacement data (generally no more than for 100 discrete targets), while the radar output maps contain thousands of pixel, each with its own time series of LOS displacements. The temporal resolution for both instruments ranges from near-real-time (duty cycles of few minutes) to long-term monitoring (duty cycles of some years). The measurement cycles are determined mainly by the type of landslide and its dynamics. Displacement range and resolution differs slightly based on the different approaches both instruments apply. GB-InSAR is characterized by a sub-millimeter detection limit whereas the total station may identify movements only in the range of few millimeters depending on the distance to the optical prism and atmospheric effects. This is due to the lower limit of detection and generally higher positional inaccuracy compared to the IBIS-L instrument.

At the upper limit, absolute movements over 100 m could be tracked with the Leica TCA2003, whereas InSAR-based techniques tend lose the original target for very large displacements. The high detection capabilities and spatial coverage of the IBIS-L comes at the cost of averaging displacements for each pixel rendering an exact (absolute) displacement measure impossible without the use of corner reflectors. On the other hand, the data acquisition for the entire field-of-view at once allows for apparent distinction of zones of high and low displacements on a qualitative level.

Topographic surveys are restricted to few discrete observations obtaining absolute measurements from within moving deposits. Since movements can be variable within just a few meters prime targets may yield more exact measurements of maximal values compared to radar derived displacements. With respect to the velocity range, a highly sensitive detection level of the IBIS-L instrument resolved Line-of-Sight displacements of only few $\text{mm}\cdot\text{h}^{-1}$ during field tests. At the Valoria landslide, an average maximum LOS velocity of about $5.8 \text{ mm}\cdot\text{h}^{-1}$ was measured in the upper and about $14 \text{ mm}\cdot\text{h}^{-1}$ in the lower part at the main flow. The automatic total station is well suited for slow ($\text{mm}\cdot\text{day}^{-1}$) to moderate ($\text{m}\cdot\text{h}^{-1}$) movements whereas it is not ideal for monitoring very slow moving landslides ($\text{mm}\cdot\text{year}^{-1}$). Using a GB-InSAR approach maintenance efforts during longer operation periods are in theory very low and field visits are required only for data retrieval. For the total station autonomous and almost maintenance-free functioning is possible on the long-term for very slow movements but when reactivations occur, frequent field visits may be necessary to reorient the prisms. A particular advantage is possibility to remotely access the computer that controls the total station ensuring long-term autonomous operation and remote collection of data.

During the years of operation the automated total station was found to be a reliable and constantly improving technology and a perspective tool for early-warning at the Valoria landslide. During landslide reactivations, measurements were taken in near real-time (3 h interval) and transmitted to an off-site computer. Based on displacement or velocity information critical movement patterns can be determined for individual prisms or for group of prisms. During autonomous operation the IBIS-L detects automatically the highest velocity of a scene between acquisitions and allows for a text message to be send in the case a predetermined threshold is exceeded.

2.4 Distributed Ground-Based Monitoring of Moderate-Moving Landslide Using Image Correlation Techniques

2.4.1 *The Principle of Image Correlation (IC) Technique Applied to Landslide Analysis*

The focus of this section is to highlight the possible applications and limitations of Image Correlation techniques applied both on terrestrial optical images and on Terrestrial Laser Scanner (TLS) point clouds. Using matching techniques, two-dimensional displacement fields can be derived by tracking objects in time series of images. The technique is based on the automatic identification of identical texture patterns within an image by maximizing a correlation function (Lewis 1995). Its principle adapted for landslide kinematics analysis is described in Delacourt et al. (2007).

Visible ground features have to be superimposed on two successive images on stable parts located outside the landslide. On the areas affected by landslide movements, the visible and recognizable features are shifted by the displacements. In order to quantify the ground displacements, a correlation window is defined on a reference (often the oldest) image. The corresponding window is searched in a pre-defined explored area belonging to the second image. The starting point of this explored area is the expected position of the window with the assumption that no displacement occurred between two acquisitions. The process is repeated for each pixel of the reference image. The Euclidean distance between the reference point and the matching point represents the displacement amplitudes in the image plane. By modifying the zone of interest, it is then possible to determine the displacements at various positions within the images. It is important to note that the normalized cross-correlation technique cannot track objects that start to rotate significantly or are affected by important perspective distortions (Lewis 1995).

The size of the correlation window is a compromise between the desired accuracy on the displacement estimates and the spatial resolution of the velocity field (Delacourt et al. 2007). An increase of the size of the correlation window ensures a good signal to noise ratio and thus a good precision, but the accuracy on the displacement estimates decreases because of their averaging on a larger correlation window. So far, Image Correlation techniques have been applied only on aerial and satellite images (e.g. SPOT, QuickBird, OrbView, EROS) for the creation of landslide displacement maps (Casson et al. 2003; Delacourt et al. 2004; LePrince et al. 2008; Debella-Gilo and Käb 2010).

The correlation results consist in matrices of displacement Δu and Δv along the u - and v -axes in the image plane with their associated correlation index. In case of orthorectified airborne images, the pixel size is constant, only the effective pixel size at the ground has to be calculated to estimate metric displacements. In case of terrestrial images, the pixel size is not constant in the image due to the oblique

acquisition; the displacements field correlated in the image plane cannot be directly interpreted in terms of metric displacements and an orthorectification procedure is compulsory for a quantitative analysis.

Several datasets of multi-source images acquired at the Super-Sauze landslide (South French Alps) over the period 2007–2010 from different platforms are analyzed to highlight the usefulness of the technique.

2.4.2 Image Correlation of Terrestrial Optical Photographs (TOP)

A set of images acquired at the Super-Sauze landslide over the period May–July 2008 is used to illustrate the potential of the technique for the characterization of the kinematics during an acceleration period (Travelletti et al. [in review](#)).

Figure 2.6 presents the monitoring system installed in front of the landslide. The instrumentation consists in a low-cost D70 Nikon reflex digital camera installed on a concrete pillar located at a distance of 300 m from the lower part and 900 m from the main scarp. The acquisition system is controlled by a datalogger powered by a 40 W solar panel. Every 4 days, a serie of images is acquired at 11:00, 12:00, 13:00 and 14:00 GMT.

Figure 2.7A details an example of displacement rates (in $\text{pixel}\cdot\text{day}^{-1}$) of the ground surface in the image plane derived from image pairs of 1–4 June 2008. The reference is the image of 20 May 2008. The contrast in displacement rates between the landslide area and the stable area gives confidence on the calculated velocity field. One can notice that the pattern of displacement rate is heterogeneous spatially and temporally. The upper part of the landslide displays the highest velocity ranging from 1 to 7 $\text{pixels}\cdot\text{day}^{-1}$ while the lower part displays velocity of less than 4 $\text{pixels}\cdot\text{day}^{-1}$. The maximum of displacement rate is observed around the 1 June 2008. Then the landslide decelerates to displacement rate of about 1 $\text{pixel}\cdot\text{day}^{-1}$. No quantitative comparisons can be carried out at this stage because the pixel sizes vary strongly in the image.

The displacement fields computed in the image plane are then orthorectified in a local geographic coordinate system by transforming the central projection of the image into an orthogonal view of the ground using the collinearity equations (Kraus and Waldhäusl 1994). The details of the methodology are explained in Travelletti et al. (2012). Figure 2.7B presents the amplitude of the 3D orthorectified displacement rates for the period 1–4 June. The difference of kinematics between the upper (until 3 $\text{m}\cdot\text{day}^{-1}$) and the lower (until 1 $\text{m}\cdot\text{day}^{-1}$) parts is important. The performance of the method has been evaluated by comparing the displacements derived from the image correlation, and the displacement monitored by dGPS on several benchmarks distributed in the stable parts and on the landslide. A correlation coefficient of $r=0.95$ is found on 219 measurements and an average relative accuracy of 20 % is determined (Travelletti et al. 2012).

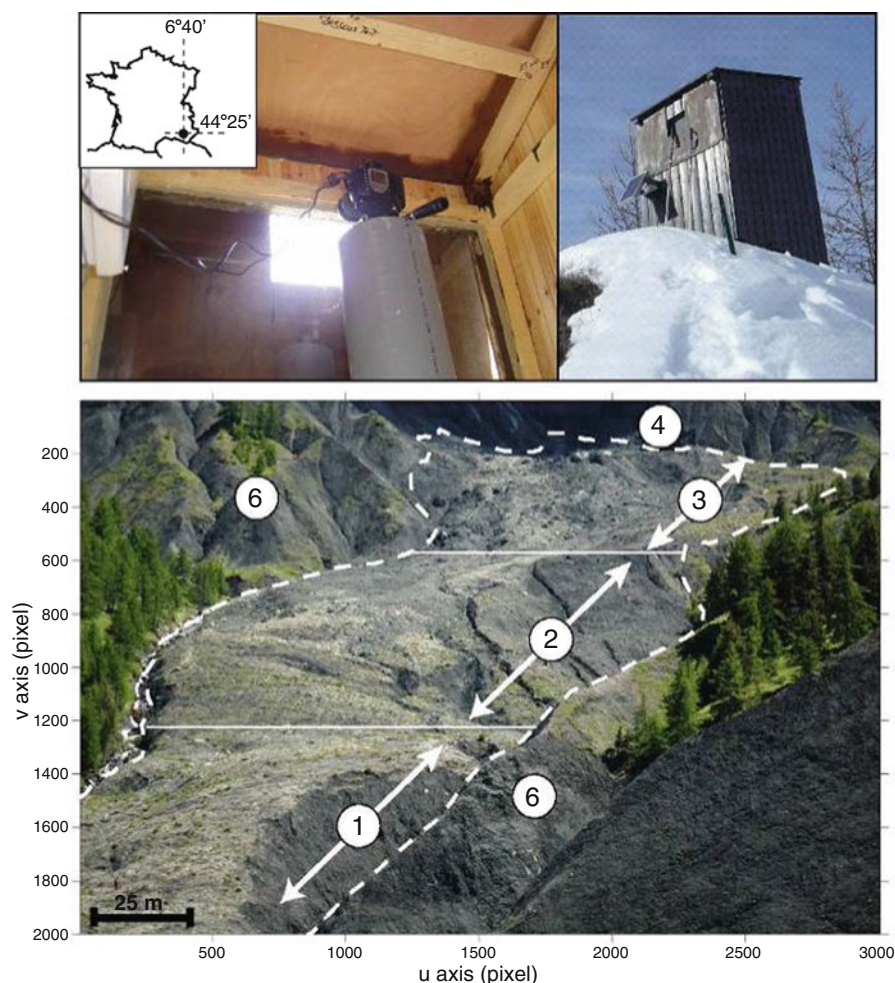


Fig. 2.6 Monitoring system with a very-high resolution camera installed in front of the Super-Sauze landslide on a stable crest. *Top*: Monitoring system. *Bottom*: Image acquired by the monitoring system presenting the different parts of the landslide from the camera location. The numbers refers to: (1) lower part (toe) of the landslide, (2) middle part (transition zone), (3) upper part (ablation zone), (4) main scarp (1,980 m), (5) front (1,734 m), (6) stable crests

2.4.3 Image Correlation of Terrestrial Laser Scanner Point Clouds (TLS)

The potential of Terrestrial Laser Scanner (TLS) for the monitoring of geomorphologic processes has been demonstrated in the last years, mainly for defining the structure of rocky slopes susceptible to rockfalls and rockslides (Abellán et al. 2009; Oppikofer et al. 2009) or characterizing the dynamics of ice glaciers

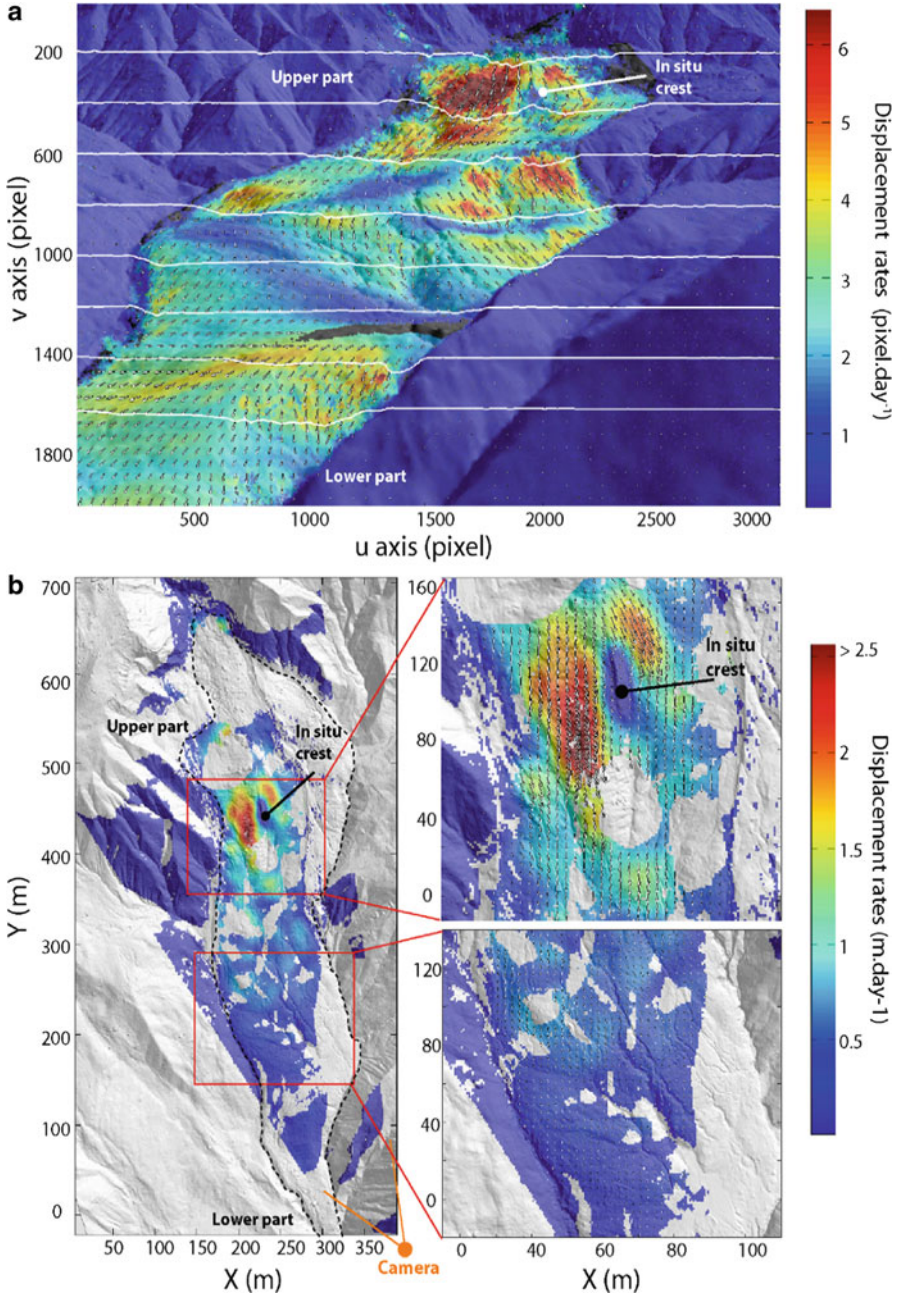


Fig. 2.7 Displacements obtained with Image Correlation for the period 1–4 June 2008: (a) Displacement rates amplitude (*color*) and direction (*arrows*) in the image plane and cumulated displacements along eight profiles crossing the landslide, (b) Displacement rates map orthorectified in the local geographic coordinate system

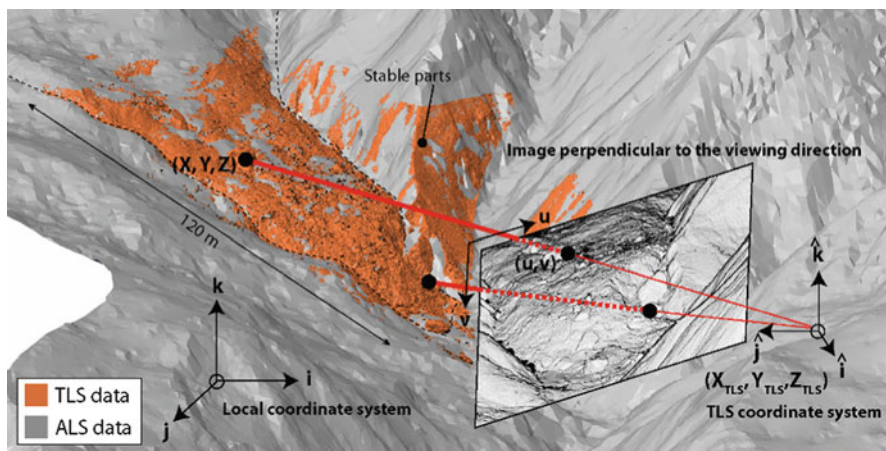


Fig. 2.8 View of the scanned area at the Super-Sauze landslide from the TLS base station, and schematic presentation of the projective projection applied on the TLS point clouds with the different coordinate systems involved in the procedure in order to produce a 2D image converted in grey-scale values. The alignment of the *stable parts* of TLS point clouds on the ALS (Airborne Laser Scanner) point cloud is indicated

(Avian et al. 2009) and landslides (Teza et al. 2008). Automatic matching algorithms applicable to TLS data have started to be developed because of their capability to fully exploit all the geometric information available in the point clouds. The approach is to find correspondences among typical features located in multi-temporal point clouds assuming that the tracked object has a constant geometry in time and/or a perfectly rigid behavior.

Image Correlation techniques can be applied on repeated TLS acquisitions in order to characterize the 3D displacement field. The hypothesis is that for objects scanned from a unique view point, simple 2D correlation functions can be applied on multi-temporal point clouds and yield the same range of accuracy than complex and time-consuming 3D surface matching algorithms (Teza et al. 2008). The performance of the cross-correlation algorithm is tested on datasets acquired at the toe of the Super-Sauze landslide. A long-range terrestrial laser scanner Optech ILRIS-3D has been used for the monitoring.

Ten acquisitions were acquired between October 2007 and May 2010 for the same base station at an average distance of 100 m from the landslide toe. The average point density at the ground surface varies from $153.0 \text{ pt}\cdot\text{m}^{-2}$ to $234.9 \text{ pt}\cdot\text{m}^{-2}$ with a standard deviation up to $351.7 \text{ pts}\cdot\text{m}^{-2}$ and a maximal density of $1,148.3 \text{ pts}\cdot\text{m}^{-2}$. A projective transformation is used to represent the entire geometrical information in a plan perpendicular to the viewing direction of the laser scan using the collinearity equations (Kraus and Waldhäusl 1994) (Fig. 2.8). The density varies from 0.78 to $0.94 \text{ pt}\cdot\text{pixel}^{-1}$ with a relatively low standard deviation of $0.18 \text{ pt}\cdot\text{pixel}^{-1}$. The distance between the point clouds to the position of the laser

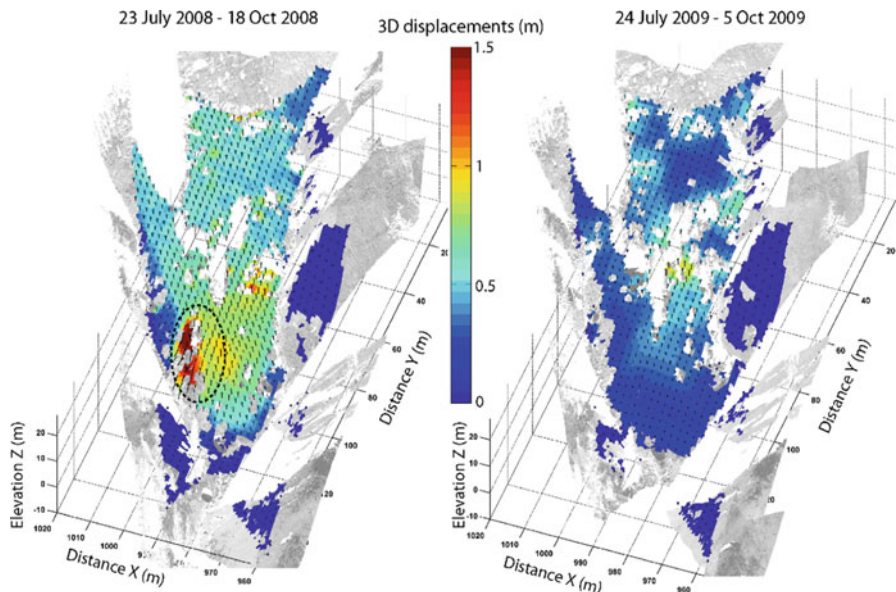


Fig. 2.9 3D displacements field obtained by TLS measurements related to the acquisition periods of July–October of the years 2008 and 2009. The *dashed circle* indicates the detachment of compartment at the front of the toe

scanner is then determined and linearly interpolated in a regular grid. The norm of the 2D gradient in u and v directions of the distance between the point clouds and the TLS station is calculated for emphasizing the morphology of the landslide. The generated images are then converted in grey-scale values (16 bits) and are used as inputs for the image correlation algorithm (Fig. 2.8).

The computed displacements are generally well reproduced for all periods. Two acquisition periods (July–October 2008, July–October 2009) are presented to illustrate the performance of the approach (Fig. 2.9). For the period July–October 2008, displacements between 0.5 and 1.5 m are observed, corresponding to an average displacement rate of $0.6\text{--}1.7\text{ cm}\cdot\text{day}^{-1}$. The displacement field displays significant spatial heterogeneities. The largest displacements are detected in the front of the toe where the slope gradient increases. The detachment of a toe compartment is also highlighted in the front.

During the period July–October 2009, the landslide displays a very different kinematics both in terms of magnitude and spatial distribution. Displacements are shorter and range from 0.1 m at the front to 0.6 m in the upper part, corresponding to an average displacement rate of $0.1\text{--}0.8\text{ cm}\cdot\text{day}^{-1}$.

The computed displacements are validated by comparing the displacement values to DGPS observations of a series of blocks easily recognizable in the TLS point clouds.

2.5 Conclusion

This section details some of the latest developments of remote-sensing techniques applied for the detection and characterization slow- to moderate-moving landslides. At regional and catchment scales, the landslide hotspot mapping through PSI analysis is an innovative approach for efficiently detecting slow-moving landslides. The approach can automatically detect clustering of PS with locally-high velocity, and a hotspot map indicating where potential mass movements exist. Future work for improvement should focus on short wavelength X-band sensors which largely increases PS density and decreases the revisit time. At the slope scale and for individual landslides, the combination of different monitoring techniques has proven to be very valuable. Since automated total stations require some days to be implemented and points of interest must be preselected, such systems are not rapidly deployable during emergency phases. However, this system is well-suited for long-term autonomous operation and collection of data at active landslides with known elements at risk. The remote sensing approach and rapid deployment of GB-InSAR makes this an ideally suited technology during crisis and rapid intervention. Image Correlation techniques applied to multi-temporal terrestrial photographs or terrestrial Laser Scanner point clouds are of particular interest for monitoring landslides characterized by annual pluri-decimetric displacements.

Considering the increasingly large fleet of remote sensing satellites operated by space agencies and private companies, and the increasing widespread of aerial and terrestrial sensors at constantly decreasing costs, the remote-sensing of landslides and risk related information encounters generally favourable data availability. One exception is currently the segment of L-band spaceborne SAR that has been demonstrated as a valuable tool for the monitoring surfaces that induce a loss of coherence with C- and X-band techniques (Strozzi et al. 2005). It is expected that very high density point clouds derived from ALS and TLS sensors will become a standard tool for landslide investigations. While it can be expected that remaining computational issues arising from large point cloud analyses will be solved as computational time becomes cheaper, many conceptual questions on the integration of high resolution DEMs in hazard and risk assessment remain (Jaboyedoff et al. 2010).

A full exploitation of the daily recorded images will not only depend on the implementation of operational processing systems but also on an easy data access and exchange via European and international networks such as GMES and GEOSS. The 'International Charter on Space and Major Disasters' has already demonstrated the advantages of a more liberal data exchange in the aftermath of major disasters. Analogous initiatives to open data archives including comprehensive time-series to a broader group of potential users appear desirable. Similarly to issues concerning easy data access, the availability of high quality software tools for the extraction of the required information is of at least equal importance. Besides proprietary software and in-house algorithms of private companies, many of such tools are also freely available on the web. This includes software for SAR interferometry

(ROI-PAC, StaMPS), open source projects with general GIS and raster processing capabilities (ILWIS, QGIS, OrbGIS). One of the most remarkable examples is probably the ORFEO (Optical and Radar Federated Earth Observation) toolbox which includes wide range of state of the art image processing tools and sensor specifications.

Major challenges for the further development of analysis methods are the integration of multi-modal and multi-temporal remote sensing datasets with existing inventory databases and in-situ measurements. Finally it should also be mentioned that the great success of collaborative mapping projects such as OpenStreetMap has raised a broad public and academic interest in the application of crowd-sourcing for many applications such as the monitoring of transportation networks, the collection of information during disaster response phases or conflict management (Goodchild 2010; Heipke 2010). Examples for the application of such community based platforms during landslide disaster already start to appear on the internet (<http://www.gawana.com/peru/ushahidi/>). They should be explored as they could yield a valuable information source that may complement “traditional” remote sensing techniques.

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