Published by AIT
the Italian Society of Remote Sensing

Multi-sensors integrated system for landslide monitoring: critical issues in system setup and data management

Cristina Castagnetti[1*], Eleonora Bertacchini[1], Alessandro Corsini[2] and Alessandro Capra[1]

[1]Department of Engineering 'Enzo Ferrari', University of Modena and Reggio Emilia,
Via Vignolese 905, 41125 Modena, Italy
[2]Department of Chemical and Geological Sciences, University of Modena and Reggio Emilia,
Largo S. Eufemia 19, 41100 Modena, Italy
*Corresponding author, e-mail address: cristina.castagnetti@unimore.it

Abstract

This paper discusses critical issues related to the reliability of topographic monitoring systems such as ATS (Automated Total Stations), GNSS (Global Navigation Satellite System) and Ground Based InSAR focusing the attention on controlling the stability of networks infrastructure, which have influence on data correction procedures but are often taken for granted, and on integrating results in GIS (Geographic Information System), under a common reference framework and with respect to open-access ancillary data. The novelty of the paper lies in the demonstration of the efficiency obtained by a proper implementation of the system. Discussion makes reference to an active landslide by using ATS, GNSS and Ground Based InSAR in continuous and periodic mode.

Keywords: Landslide monitoring, integrated systems, critical aspects, GNSS, Total Station, GB-InSAR.

Introduction

In geomatics, a consolidated approach for integrated surface displacement monitoring of unstable slopes is the creation of a network of benchmarks surveyed by Global Navigation Satellite System (GNSS) and by Automated Total Stations (ATS) [Aloisi et al., 2003; Gunzburger et al., 2005; Puglisi et al., 2005; Mattia et al., 2007; Bertacchini et al., 2009]. A more innovative remote sensing approach is the use of Ground Based InSAR (GB-InSAR) [Tarchi et al., 2003; Pieraccini et al., 2006]. These systems can be operated in periodic mode, with repeated operator-based surveys, or in semi-continuous mode, by deploying permanent GNSS receivers, ATS and GB-InSAR devices in the field and by controlling data acquisition, data processing and data transmission cycles using dedicated computing units and broadband connectivity. Even if technological development has boosted the performances of individual monitoring devices and has made them increasingly user friendly, the design-phase of a monitoring network integrating

European Journal of Remote Sensing - 2013, 46: 104-124
doi: 10.5721/EuJRS20134607

GNSS, ATS and GB-InSAR is still the crucial point for obtaining precise, accurate and comparable monitoring results. The design-phase should consider conditioning factors related to the physiographic conditions at the monitored site, to the hardware configuration of the monitoring network and to the differences between native reference frames adopted by each instrument. For instance, neglecting an issues such as the control of the stability of mounting shaft and/or pillars for the ATS, GNSS master or GB-InSAR and of the ATS prisms serving as references for data correction, can undermine the overall reliability of the monitoring network. At the same time, the integration of monitoring results in a common spatial reference framework must be carefully evaluated, taking into consideration that any transformation operation introduces errors that must be minimized by performing the proper operations in the field. Equally important is to evaluate the adequacy of open-source GIS (Geographic Information System) ancillary data such as Google Earth images and Shuttle Radar Topography Mission (SRTM) Digital Terrain Models (DTMs) for an effective spatial integration of monitoring results, as this can be crucial when sites with no previous background information have to be monitored.

This paper aims at discussing the above mentioned issues by making reference to the methods adopted and the results obtained from 2007 to 2011 by monitoring with GNSS, ATS and GB-InSAR an active landslide located in the northern Apennines of Italy that poses threat to several elements at risk and that, as a consequence, has been of relevance for civil protection and land use planning authorities. Particular emphasis was given to the GB-InSAR maps projection and geo-referencing process by analysing the role played by the resolution of digital elevation models. These issues, indeed, are still an open research field and the paper aims at providing progress for it.

Case study settings

The Valoria landslide is a complex earth slide – earth flow located in the northern Apennines of Italy, in the Secchia River basin [Manzi et al., 2004; Corsini et al., 2005; Borgatti et al., 2006; Ronchetti et al., 2007]. The landslide extends from about 1400 m to 500 m a.s.l. over a length of about 3.5 km, covering an area of more than 1.6 km^2 (Fig. 1). Bedrock is made of Cretaceous to Miocene sandstone flysch and clayshales, while the landslide body is made of clay, silt and blocks forming a deposit with a detrital texture and a matrix supported fabric whose maximum thickness is about 30 m. Despite its prehistoric origin [Bertolini et al., 2005], the landslide resumed activity several times during the last 60 years and has been seasonally active from 2001 to date [Ronchetti et al., 2007]. The geomorphic evolution of the slope was particularly relevant in winter-spring 2001, 2005, 2006 and 2009 [Corsini et al., 2009; Sterzai et al., 2010]. In these years, total reactivations of the landslide were triggered by 150 to 350 mm of rainfall in periods ranging from 3 to 40 days [Daehne, 2011]. Reactivations of the landslide threatened a number of elements at risk (Fig. 2): some sparse houses (which were temporarily evacuated), a province road crossing the landslide's track zone (which was destroyed several times until a bridge was built in 2008 for crossing the moving mass), a gas pipeline in the crown zone (which was relocated several times) and the Dolo river at the base of the slope (which was partially dammed by slope movements in 2001 and 2009). As the structural mitigation of such a large scale landslide is practically impossible, landslide monitoring was required by civil protection authorities for risk management since 2001. Monitoring was based on geotechnical instrumentation from 2001 to 2007 and on a topographic monitoring network from 2007. Topographic superficial monitoring is based on GNSS and ATS that were integrated by GB-InSAR for a short period in 2009.

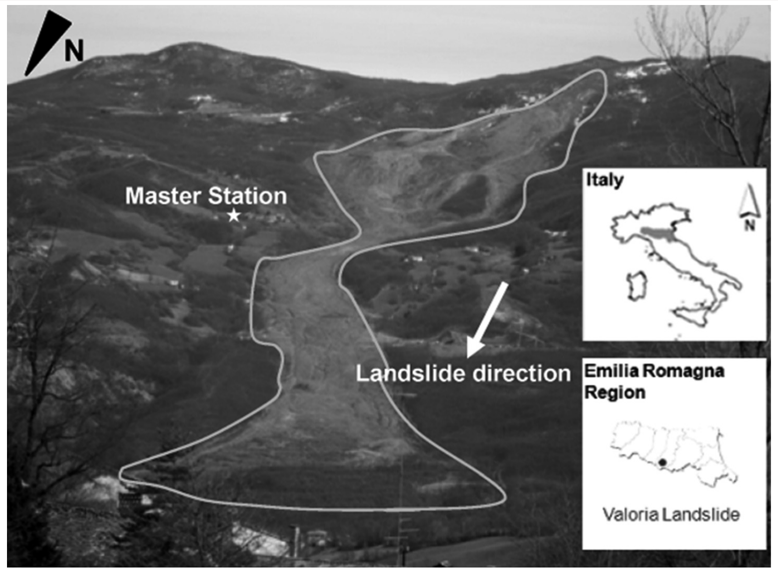

Figure 1 - Location and overview of the Valoria landslide (November 2009).

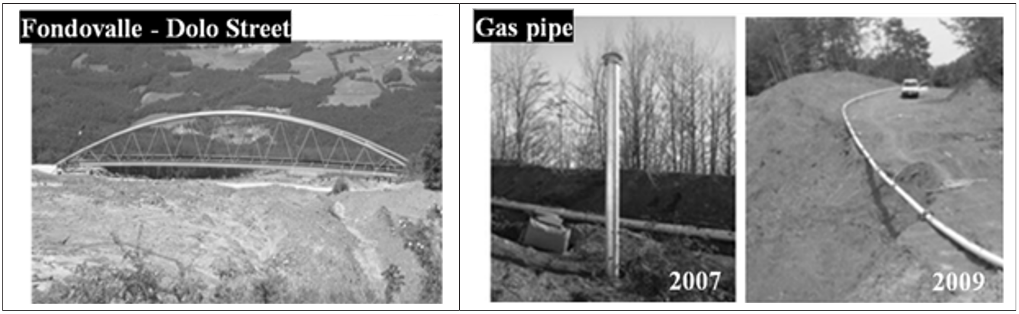

Figure 2 - Critical elements of the Valoria landslide: the bridge on the left and the gas pipe on the right. The crown zone, where the gas pipe is located, is extremely changed since 2007, when GNSS benchmark n. 11 was installed, to 2009 when the benchmark was lost.

Methods

Global Navigation Satellite System (GNSS) monitoring

GNSS monitoring of landslides requires the availability of a master station on a stable position outside the unstable slope and the monumentation of a number of rover benchmarks in the landslide area. This configuration is used when the purpose is to detect both intrinsic deformation and absolute displacement of the landslide with respect to a stable point (relative positioning technique). Mandatory requirements are a sufficient satellites visibility and a fix coupling between the GNSS benchmark and the ground. The GNSS monitoring network in Valoria includes 1 reference station and 11 rovers. Master and rovers were coupled to the ground using 3 m long hollow aluminium poles driven in the ground for 1.5 m and then filled with concrete in order to increase stability (upper Figs. 3, 3c and 3d). The master pole is coupled to a reinforced concrete foundation slab about 1 m thick. A forced centring device was used to assure repeatability of GNSS antennas positioning (Fig. 3a, 3c, 3d). The master station was located at a geologically stable site (site “Are Vecchie”) which is at a maximum distance of 1.5 km from rovers (short baselines). The distribution of rovers in the landslide reflected the distribution of geomorphic units that needed to be monitored and it took into consideration the need for an homogeneous spatial distribution of rovers with respect to the master station (Fig. 4).

a) Reference point R2

b) Monitoring prism

c) GNSS monitoring point - continuous

d) GNSS monitoring points- periodic

Figure 3 - Master station of the monitoring system at “Are Vecchie” in the upper part of the image: from left to right GNSS reference station, wireless sensor, PC unit for remote control, bi-directional clinometer and ATS. Below examples of points monumentations.

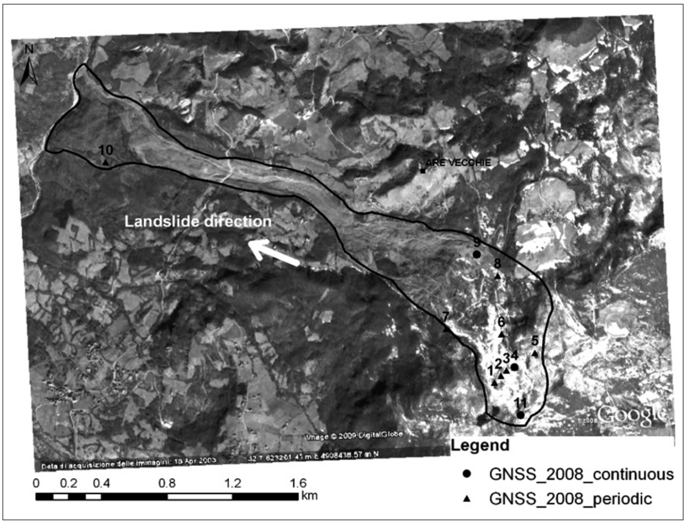

Figure 4 - Satellite imagery of the Valoria landslide (Google Earth, 2003) with overlapped the location of GNSS rovers at 2008.

Table 1 - Main characteristics of periodic campaigns.

Instrument	Monitoring	Points	Dates	N° of campaigns
GNSS	Periodic	11 rovers + 1 reference	27 November 2007 12 December 2007 22 January 2008 22 June 2010	4
GNSS	Continuous	3 rovers+1 reference	Since May 2008	/
ATS	Periodic	29 monitoring prisms + 6 reference prisms	12 October 2007 23 October 2007 12 November 2007 5 December 2007 12 December 2007 21 December 2007 7 January 2008 18 January 2008 26 February 2008 19 March 2008 25 March 2008	11
ATS	Continuous	35 monitoring prisms + 6 reference prisms	Since May 2008	/
GB-InSAR	Periodic	Upper portion of the landslide	23-24 February 2009	1
GNSS for stability check	Periodic	ATS, R1, R2	14 December 2007 12 July 2011	2

The GNSS network was operated in periodic mode (11 rovers plus the master) from 2007 to 2010 and in continuous mode (3 rovers plus the master) from 2008 to 2012. Periodic GNSS monitoring consisted of four fast static campaigns between 2007 and 2010 (27 November 2007, 12 December 2007, 22 January 2008 and 22 June 2010). Surveys were performed with double frequency receivers at the master and at the rovers. Post-processing was carried out with commercial software Leica GEO Office v.4.0 using the master station data as reference. A summary of periodic GNSS campaigns is given in Table 1.

Continuous GNSS monitoring was carried out between 2008 and 2012. On the basis of movements recorded by periodic GNSS campaigns, rovers 11, 9 and 4 were selected for continuous monitoring (Tab. 2). Benchmark 11 (pictured in Fig. 2) was representative of an active earthflow area, as it moved about 40 cm over 2 months of periodic campaigns in 2007. Benchmarks 9 and 4 were representative of potential enlargement areas of the landslide's source zone. Hardware configuration included 1 double frequency receiver at 1 Hz at the master station and 3 single frequency GNSS receivers at 1 Hz acting as rovers streaming data wirelessly to the master station (Tab. 3). At the master station, a computer unit was used for data storage, real-time processing and remote access by GPRS router connection. The Leica software GNSS Spider was used for hourly and daily RINEX files creation and hourly baselines distance computation.

Table 2 - GNSS periodic campaigns: resulting displacements (Δ represents the total displacement while ΔE, ΔN, Δh refer to the displacement components in East, North and Up respectively).

	01/2008-11/2007				06/2010-01/2008			
	ΔE [m]	**ΔN [m]**	**Δh [m]**	**Δ [m]**	**ΔE [m]**	**ΔN [m]**	**Δh [m]**	**Δ [m]**
1	0.00	0.11	-0.04	0.11	--	--	--	--
2	-0.03	0.03	-0.01	0.04	--	--	--	--
3	-0.01	0.00	-0.03	0.04	--	--	--	--
4	-0.00	-0.04	0.00	0.02	-73.11	16.13	-24.92	78.91
5	0.00	0.02	-0.01	0.02	0.01	0.07	-0.02	0.07
6	-0.01	-0.01	0.02	0.02	-0.20	0.14	-0.19	0.31
7	0.00	-0.01	-0.01	0.02	-0.03	0.08	-0.08	0.11
8	-0.00	0.00	0.02	0.02	-0.07	0.08	-0.09	0.14
9	-0.00	-0.00	0.00	0.00	0.70	1.43	0.19	1.60
10	0.00	-0.01	-0.03	0.03	-21.80	7.03	-0.18	22.90
11	-0.14	0.30	-0.30	0.44	--	--	--	--

Automated Total Station (ATS) monitoring

ATS monitoring of landslides requires the availability of a stable position outside the unstable slope for installing the total station and the installation of a number of reflectors (prisms) in the landslide area and on stable positions (the latter serving as control points for data correction). Mandatory requirements are the inter-visibility between the total station and the prisms, the stability of the total station and of the control prisms and the direct coupling between the monitoring prisms and the landslide ground. In Valoria, the ATS was installed next to the GNSS master station using a reinforced concrete pilaster about 1.60 m high, coupled to the same foundation slab used by the GNSS master (upper Fig. 3). A forced centring device was used to assure repeatability of ATS positioning. Monitoring prisms were installed within the landslide by fixing them to 2 m high steel rods of 20 mm diameter driven into the ground for at least 1 m (Fig. 3b). At the same time, control prisms were installed outside the landslide for computing corrections parameters (Fig. 5). Control prisms were deployed radially from the ATS, at a distance range larger than the distance range of monitoring prisms. Control prisms were installed using either a forced centring device (for allowing to change the prism with a GNSS antenna in order to check for their stability by means of GNSS periodic campaigns, see Fig. 3a) or by using special mounting for installation on walls and houses.

Table 3 - Technical parameters of the integrated topographic monitoring system.

ATS	**Description**
Model	TCA 2003 by Leica Geosystems
Maximum operating distance	2000 m
Angular accuracy	0.5” (0.15 mgon)
Distance accuracy	1 mm + 1 ppm / 3.0 s
Survey Targets	41 prisms: 35 within the landslide and 6 outside it for control
External communication	GSM modem / satellite link
Acquisition	every 3 hours
GNSS	
Master Station	1 dual frequency receiver GMX902 GG by Leica Geosystems, antenna AX1202 GG by Leica Geosystems (power supply with back-up battery)
Rover	3 single frequency receivers GMX901 GG by Leica Geosystems with integrated antenna (solar panel + external battery)
Configuration	1Hz logging rate, 10 degree for the cut-off angle
Data Transmission Link	Continuous data streaming by WLAN
Bi-directional clinometer	
Model	Nivel 210 by Leica Geosystems
Resolution	0.001 mrad
Accuracy	± 0.0047 mrad
Temperature sensor	Yes
Sampling interval	1 minute
Position	On the ATS pilaster at a height of 1 m
PC unit	
ATS/GNSS integration	Software: Geomos and GNSS Spider by Leica Geosystems
Power Supply	220 V CA with 12 A back-up battery
Remote Data Transmission	GPRS modem connection

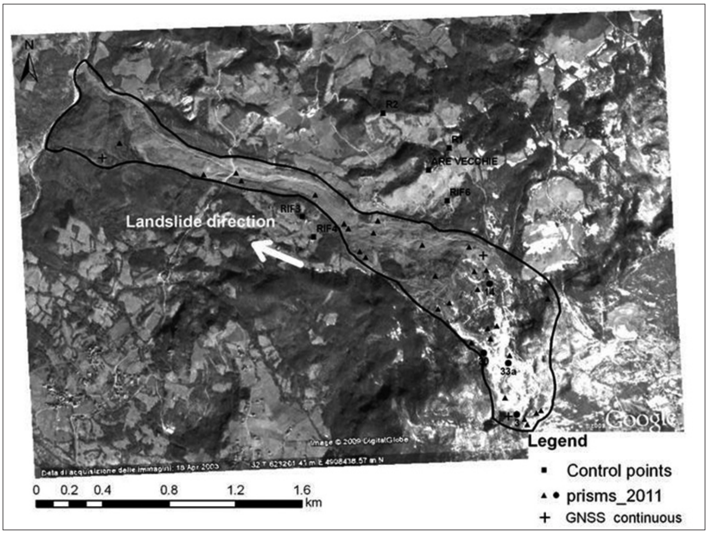

Figure 5 - Satellite imagery of the Valoria landslide (Google Earth, 2003) with overlapped the location of monitoring points at November 2011.

The ATS network was operated in periodic mode from 2007 to 2008 and in continuous mode from 2008 to 2012. In periodic mode, 11 ATS measurement campaigns were performed using 6 reference prisms and 29 monitoring prisms (Tab. 1). Each campaign was characterized by 3 repetitions of measurements. Redundancy allowed to check for the consistency of each set of measurements during post-processing. In continuous mode, 3 hours interval ATS measurement campaigns were performed using 6 reference prisms and about 35 monitoring prisms. The number of monitoring prisms varied in time, as landslides movements buried prisms and new ones were installed as substitutes or integration. The spatial distribution of prisms at November 2011 is shown in Figure 5 (note that the further away reference prism RIF5, located 1.5 km North from the ATS position, is not shown in figure for map readability purposes). The ATS was controlled by Leica Geomos software running in the computer unit used also for continuous GNSS. Raw observations were corrected for atmospheric errors by using data from reference prisms. The correction algorithm computes ppm (part per million) corrections by comparing the known initial distance between ATS and reference prisms to the distance measured during each cycle (Tab. 3).

The stability of ATS and of the control prisms was periodically checked in order to avoid misinterpretation of results. The stability of ATS is essential to guarantee the stability of the reference frame and the consistency among subsequent observations. The stability of control prisms is of great concern because their coordinates are used to compute geometric corrections which are then applied to all raw measurements. Periodic surveys were carried out by means of GNSS static sessions in order to compute the network adjustment and estimate ATS and reference prisms coordinates with high accuracy (about 1÷1.5 cm). Particularly, GNSS surveys were carried out by positioning receivers on the ATS pillar (in 2007 and 2011) and on R1 and R2 reference prisms installations (in 2009 and 2011). These measurements played a key role in the geo-referencing process as well. The network adjustment provided solutions which were referred to the master GNSS.

The stability of ATS was also kept under control by a bi-directional clinometer which was installed on the pillar with the aim of checking the tilt of the installation. The time series of tilt values showed that the errors associated to repeated re-levelling of the ATS is in the order of 1 cm (Fig. 6).

Ground Based InSAR (GB-InSAR) monitoring

A GB-InSAR monitoring campaign was carried out between 23-24 February 2009 by means of a IBIS-L instrument, whose main characteristics are in Table 4. The instrument was installed for about 24 hours nearby the master station of the GNSS and ATS monitoring system. The Line of Sight (LoS) pointed to the upper part of the landslide and about 8 images per hour were acquired (Tab. 5).

The estimation of atmospheric influence is essential when processing GB-InSAR signal [Pipia et al., 2006; Pipia et al., 2008]. IBIS Guardian Software v. 01.02 was used for atmospheric correction and motion estimate. The first 27 scenes were used to define the calibration set using a coherence threshold of 0.65, resulting in about 365.000 pixels above the imposed threshold. Displacements were computed by stacking of all of the acquired scenes.

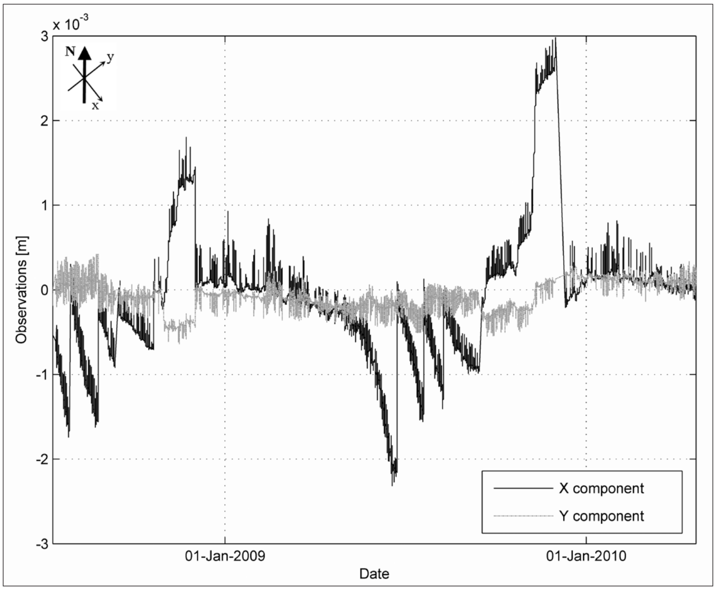

Figure 6 - Time series of bi-directional clinometer observations (X in black, Y in gray).

Table 4 - GB-InSAR technical characteristics - IBIS-L datasheet.

Instrument Parameter	Description
Frequency	Ku band (available also in X band)
Radar type	SF-CW
Operative range	[10 - 4000] m
Range resolution	0.75 (0.5) m
Cross-range resolution	~ 4.4 mrad
Displ. accuracy	up to 0.1 mm
Acquisition time	≥ 5 min
Phase ambiguity limit	~ 4.4 mm

Table 5 - GB-InSAR survey details.

Survey parameters	Values
Date	23 Feb. (h 15.35) - 24 Feb. (h 14.57)
Distance to slope (m)	Up to 1600 m
Horizontal antenna Aperture (degrees)	38
Range resolution (m)	0.5
Cross-range resolution (mrad)	4.4
Acquisitions per hour (number)	8
Duration (h)	About 24 h

Spatial Data Integration

Spatial data integration in GIS requires the adoption of a common reference framework for results obtained by different sensors. GNSS data are originally referred to ETRF2000 (European Terrestrial Reference Frame, computation epoch 2008.0). ATS results are originally referred to a local reference system centered at the ATS position and oriented to one reference prism. GB-InSAR results are originally referred to a local reference system centered at the GB-InSAR position and oriented to the LoS. Open access ancillary data such as Google Earth imagery or SRTM digital elevation models are provided in other different reference systems, which are the local image reference frame and WGS84 (World Geodetic System 1984) respectively. The local image reference frame is based on pixel number (rows and columns) and is then geo-referenced to be the GIS basic map for display purposes.

In this work, the selected reference frame for GIS integration was ETRF2000 with UTM (Universal Transverse Mercator) cartographic projection. It should be pinpointed that the choice of using open-access ancillary data for GIS integration is based on the consideration that these data can be readily available virtually in any part of the Italian territory. Therefore, in case of disasters, authorities can quickly download the SRTM DTM to re-project GB-InSAR displacement maps or use Google Earth imagery to immediately visualize results in a GIS. To geo-reference ATS results, static GNSS surveys of about 8 hours were carried out by positioning double frequency receivers on the ATS pilaster in 2007 and 2011 and on two control prisms (R1 and R2) in 2009 and 2011. This allowed fixing the ATS instrument coordinates and to compute rotation of the orientation angle by using the coordinates of two reference prisms. To geo-reference GB-InSAR results, a fast static GNSS survey was performed to define the position of the radar, while orientation of the LoS was defined by a compass. As the GNSS survey was processed with respect to the local GNSS master station, the very short baseline allowed a radar positioning accuracy of about 1÷2 cm to be obtained. GB-InSAR images were then re-projected on the SRTM DTM in ETRF2000 coordinates. The SRTM DTM is characterized by a cell size of 90 m. For the purpose of displaying GB-InSAR data, it was re-sampled with a cell size of 5 m. This does not improve the accuracy of the DTM itself but allows to better re-project the GB-InSAR displacement map by using a similar cell resolution for the DTM and the radar map. Google Earth imagery were geo-referenced by picking the ETRF2000 coordinates of several homologous points distributed all over the image.

Results

GNSS and Automated Total Station monitoring

The ATS monitored several reactivations of the earth flows. The final accuracy of ATS results was estimated at ± 5 cm (confidence level 68%) by considering the nominal accuracy of ATS (1 mm+1 ppm, which means about 2÷3 mm at a distance of 1.5 km, see Tab. 3), the atmospheric influence on Electronic Distance Meter (EDM) (up to 3÷4 cm at a distance of 1.5 km) and the periodic tilting of the ATS pilaster (less than 1 cm).

This relatively low accuracy level was acceptable for active prisms that moved several cm or meters in a few days (i.e. prisms 14 and 33a in Fig. 7), while it was a problem for prisms affected by lower movement rates (i.e. prisms 3 and 30 in Fig. 8). In this latter case, long time series were required before movement trends could be detected.

Significant displacements were recorded with periodic GNSS surveys. From March 2008 to June 2010, rover 4 moved about 80 m while rover 10 moved several meters (Tab. 2). On the contrary, no significant movements were detected by continuous GNSS monitoring, whose accuracy can be estimated in about 2÷3 cm by considering near real-time processing with respect to the master GNSS located at a distance of about 1 km from rovers. The time series of GNSS rover 9 is shown in Figure 9: the linear interpolation does not highlight any significant movement trend. This allows to state that no enlargement of the landslide occurred at rover 9 position over the monitored time span. Rover 11, on the other hand, was lost in 2009 due to the sudden and rapid landslide reactivation a few months after installation of continuous GNSS devices. A new continuous GNSS benchmark was created in 2010 at the crown zone in substitution of rover 11, but the new point did not move significantly ever since. Rover 4 was also damaged by landslide reactivation in 2009, few months after installation of continuous GNSS devices. Devices were recovered but no longer installed on site, and rover 4 benchmark remained measurable for periodic surveys only.

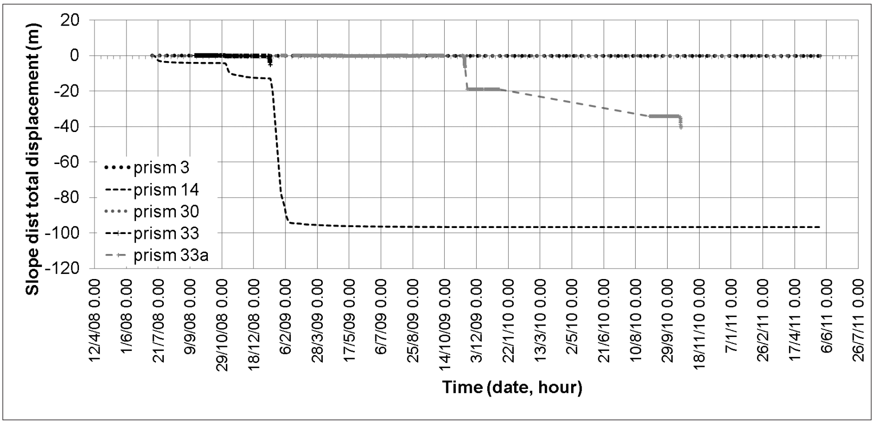

Figure 7 - Cumulative displacement of some prisms belonging to the crown zone (3, 14, 30, 33, 33a) by observing the slope distance.

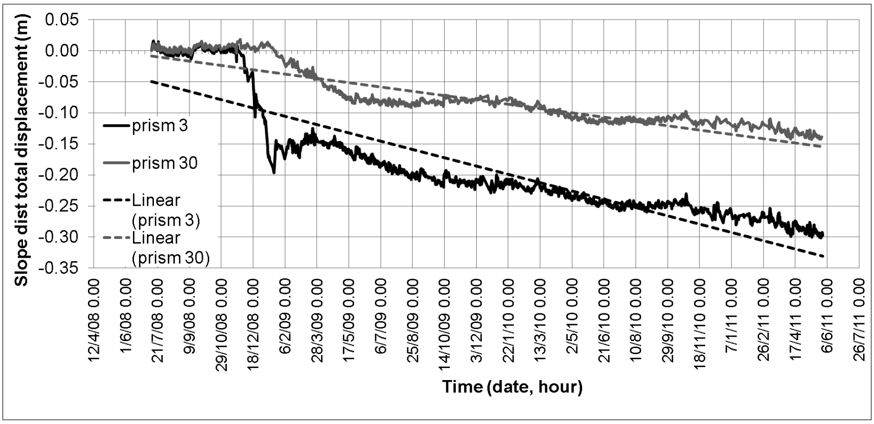

Figure 8 - Focus on cumulative displacement of prisms 3 and 30 in the crown zone: time series of slope distances and respective linear interpolations.

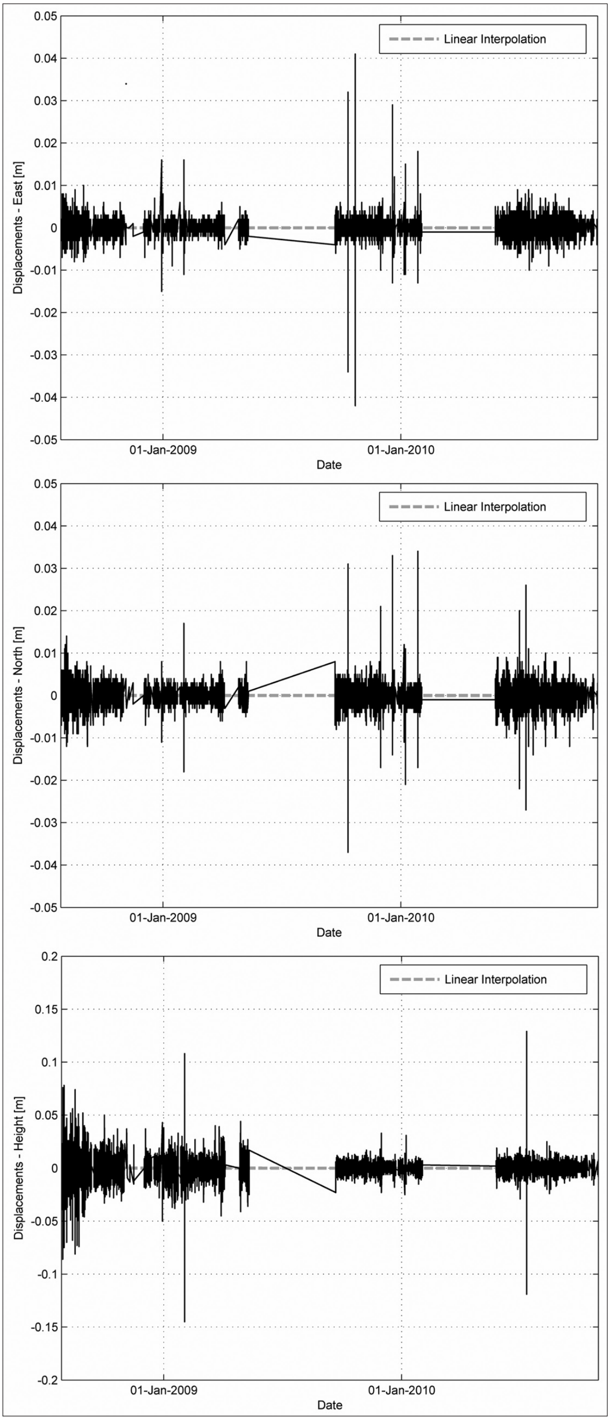

Figure 9 - Time series of GNSS rover 9: from the top East, North and Up components. The linear interpolation highlights that no significant displacement occurs.

Ground Based InSAR monitoring

GB-InSAR monitoring results referring to the upper landslide zone are represented by the LoS displacement map of Figure 10. Conventionally, in ground based interferometry, LoS displacement is positive if the pixel moves away from the sensor and it is negative if the pixel moves towards the sensor [Skolnik, 1990; Hanssen, 2001]. Given the acquisition geometry, negative LoS values in Figure 10 correspond to down slope movements. Maximum displacement (represented in red) was over 400 mm in about 24 hours. The map in Figure 10 shows also the locations of ATS prisms and the location of some points for which displacement time series were obtained. Examples of LoS displacement time series are represented in Figure 11 and Figure 12 (two separate plots are used in order to show time series at a proper scale). Displacement trend is well identified in all points, even if some, such as g3 and g31, show a rather scattered plot.

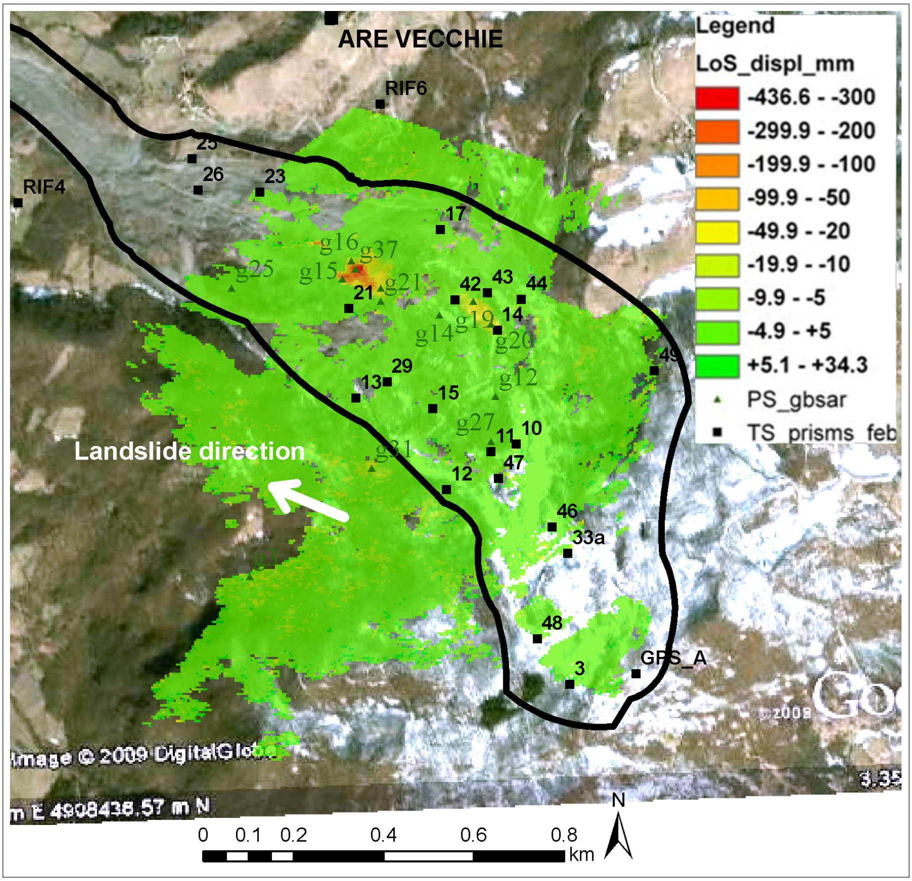

Figure 10 - LoS displacement map with overlapped the locations of prisms (23 Feb. 2009) and permanent scatterers. The black line shows the landslide boundaries.

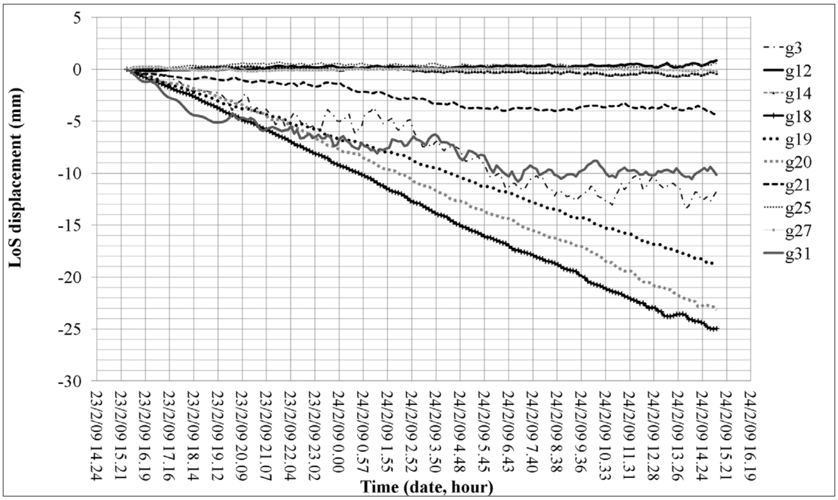

Figure 11 - Examples of LoS displacements (magnitude< 30 mm).

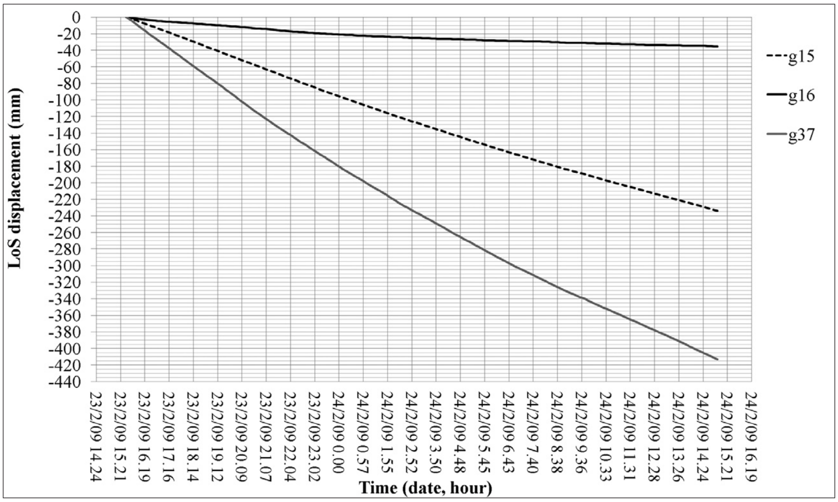

Figure 12 - Examples of LoS displacements (magnitude > 30 mm).

Discussion

Stability of ATS pillar

One of the most important critical aspect to take into account is the stability of the ATS monumentation, as variation in time of the centre position of the ATS can lead to misinterpretations of actual movements of the prisms within the landslide. The final accuracy of ATS results can be improved by considering disturbances affecting ATS pilaster. This is mandatory in case displacement at the pillar top due to tilting or other instability phenomena is of the same order of magnitude of the expected landslide displacement. Moreover, each re-levelling operation that is necessary to maintain the ATS into the operative tilt range, might change the position of the ATS reference frame origin. ATS measurements are generally automatically compensated for tilting on the basis of the internal tiltmeter. However, this is not alone sufficient to ensure that measurements are referred to the same instrumental centre, as a rigid translation without tilting might also occur due to local unfavourable conditions.

In Valoria, a bi-directional clinometer was installed on the ATS pilaster to detect local disturbing effects with higher accuracy with respect to the internal ATS tiltmeter and repeated GNSS measures of the pillar position were performed in 2007 and 2011 for assuring that no rigid translation had occurred. The clinometer time series (Fig. 6) shows that the pilaster underwent cyclic tilting over time, particularly along the x component, probably due to changes in moisture content of the foundation soil. Re-levelling was necessary several times in order to avoid the ATS stop working or the measurements to be taken out of proper operative ranges. Steps due to re-levelling of the ATS are well visible in the tilt plot. If the recorded tilt values are converted into displacement by considering the pillar's height, a maximum deviation from zero in the magnitude of few mm is obtained (see Fig. 6). As the expected movements in Valoria were larger than some centimeters, the periodic tilting of the pillar did not undermine the geomorphic significance of ATS observations, so no correction really needed to be applied to raw data. However, this offset might be of serious concern when very high precision displacement monitoring is required. Another factor that helped reducing the negative effect of tilting was its seasonality (by tilting back and forth through seasons, the resulting final position of the ATS was very similar to the initial one) and the absence of a rigid translation of the pillar on its base. This was confirmed by the comparison between the coordinates obtained in 14/12/2007 and 12/07/2011 by periodic static GNSS surveys of the ATS pillar, which did not show any significant displacement of the pillar over time (see Tab. 6).

Table 6 - Resulting coordinates of ATS pillar, R1 and R2 installations provided by GNSS periodic surveys (UTM ETRF2000 reference frame). The stability is verified in all components: East, North and Up.

Point ID	Survey Date	E [m]	N [m]	Up [m]
ATS	14 December 2007	623660.13	4908891.65	1086.72
ATS	12 July 2011	623660.13	4908891.66	1086.70
R1	16 October 2009	623782.56	4909024.93	1081.73
R1	12 July 2011	623782.56	4909024.94	1081.71
R2	16 October 2009	623385.15	4909232.71	1017.10
R2	12 July 2011	623385.14	4909232.72	1017.08

Stability of ATS control prisms

It is widely known that the reliability of ATS measurements regarding monitoring points is strictly connected to the atmospheric influence on the EDM measurements [Marini and Murray, 1973]. The atmospheric influence increases together with distance and can achieve some centimetres of magnitude if no correction is introduced [Rüeger, 1990]. A rigorous geodetic approach for taking into account the atmosphere influence would require computation based on the Barrell-Sears model [Barrell and Sears, 1939] which accounts for meteorological parameters (temperature, pressure, humidity) [Bertacchini et al., 2011]. This is mandatory when small displacements have to be monitored. In Valoria that was not the case, so corrections were based on the assumption that reference prisms located outside the landslide remain stable through time. In that case, comparing values of distance and angle of reference prisms at the initial epoch (i.e. t0) to values obtained in following measurement cycles of the same reference prims (i.e. t1, t2, and so on) allows to compute correction factors proportional to distance that are then applied, in each cycle, to all prisms of the network. With this monitoring approach, which is substantially different from traditional geodetic approaches, it is very important to check if the reference prisms which are used to compute corrections are effectively stable or not. In that framework, the seasonal measurement of the absolute coordinates of reference prisms helps to detect the mean seasonal effects of atmospheric changes and reduces the impact of a rough correction on final observations.

In Figure 13 the EDM measurements over three years for the reference points R1, R2, RIF4 and RIF5 is shown. The time series clearly highlight a variation of distance values with both yearly and seasonal period, with the maximum variation being about ±2.5 cm. The amplitude of the variation increases from R1 to RIF5, being directly proportional to the measured distances, that are respectively from 180 m to 1430 m. By performing periodic GNSS static surveys upon reference prisms R1 and R2 in 16/10/2009 and 12/07/2011, it was proven that the absolute coordinates (whose accuracy is about 2 cm) of the prisms did not vary through time (see Tab. 6) so the prisms were actually stable and ATS distance variations were due to atmospheric effects only.

Performing periodic GNSS surveys on reference prisms R1 and R2 were also useful for checking the invariance of the ATS angular reference system, as ATS angle measurements might drift in time due to the device's fatigue. Given that no significant movements were detected for R1 and R2, the computed transformation parameters (translations and rotation) proved suitable for correct geo-referencing of ATS measurements.

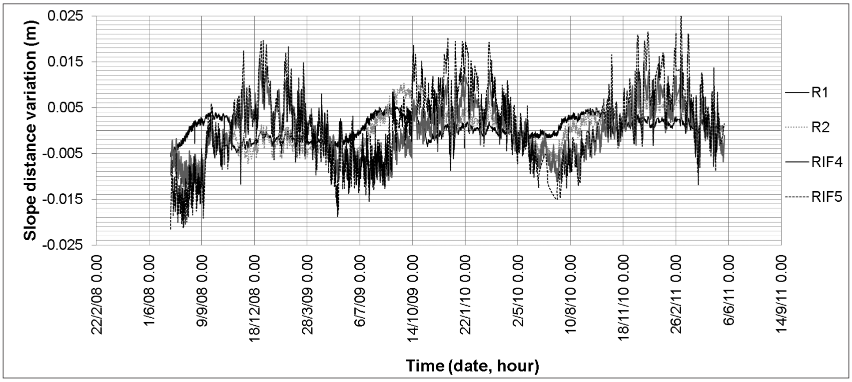

Figure 13 - Time series of EDM measurements for reference prisms.

Transformation to a common reference coordinate system for GIS integration

The GNSS, ATS and GB-InSAR systems work in different native reference frameworks. Coordinates transformations have to be performed in order to integrate results in the GIS, which may be very useful to display monitoring results with respect to ancillary geographic, morphologic and geologic data. It is known that transformation of data from one coordinate framework into another might introduce errors and reduce the accuracy of results [Watson, 2006]. It is therefore advisable to process and correct measurements of each individual instrument by using its own reference framework and then to transform the computed displacement results from one reference framework to another. This was the approach adopted in Valoria, where displacement results were transformed to ETRF2000 after being processed in their own reference framework. An exception was, obviously, GNSS results, that are natively in ETRF2000.

The local reference frame of ATS in Valoria was originally centred at the instrument centre and oriented to R2 reference prism. The GNSS static measurements performed at the ATS pillar and at R1 and R2 reference prisms allowed rotating the local reference framework to the geographic North and transforming it to the ETRF2000.

The local reference frame of GB-InSAR in Valoria was originally centred at the instrument centre and oriented to the LoS (range direction). The operation of geo-referencing LoS displacement maps obtained with GB-InSAR data is quite critical, as the pixel size of GB-InSAR scenes varies with range distance [Skolnik, 1990; Hanssen, 2001]. With the IBIS-L Ku band radar used in Valoria, the cell size was about 4.4 m by 0.5 m at 1 km distance. This means that if a comparison between LoS displacement map and ATS and GNSS results is required, a geo-referencing error of only 1 pixel might undermine the reliability of the comparison. Geo-referencing to ETRF2000 was based on the fast static GNSS survey of the IBIS-L centre, whose accuracy is 1÷2 cm. The angular orientation to the North was obtained by a compass with a 1/10th degree resolution. A more accurate orientation of the GB-InSAR displacement map could have been achieved by using corner reflectors and by measuring their position with GNSS.

Due to the relatively low accuracy of the adopted positioning and orientation procedure, which was however still much smaller than the size of the GB-InSAR image pixels, a geo-referencing consistency check was performed by comparing GB-InSAR displacement results to ATS measurements. Results from both techniques could be compared thanks to the significant rate of landslide movements during the survey. As the radar was installed at only 2 m distance from the ATS, the LoS of the radar is practically coincident to the line along which the ATS measures the slope distance of prisms located within the radar scene. The critical issue to be addressed in this comparison process is that, inevitably, an uncertainty remains in identifying the exact pixel, in the GB-InSAR image, corresponding to a given specific ATS prism. However, while it is not possible to state the uniqueness of the selection, it is possible to pinpoint that if movements recorded by ATS are in the order of magnitude of these recorded by GB-InSAR, then the geo-referencing process of LoS displacement maps should be considered satisfactory. Figure 14 shows some examples of the comparison of displacement time series. Slope distances show that prisms 13 and 14 did not move over the monitoring time span, in accordance to the LoS displacement results obtained by selecting permanent scatterers in correspondence of these prisms. On the other hand, prism 21 moved about 14 mm and the LoS displacement of a corresponding permanent scatterer showed about 13 mm.

Another issue with geo-referencing LoS displacement maps, is that they need to be re-projected over a terrain surface in order to transform range distances into ground distances, and this is generally achieved by projecting data over a DTM. One open question is how the resolution of the adopted DTM affects the projection, and hence the geo-referencing of the results. For a qualitative estimation of changes in the spatial distribution of LoS displacement values resulting from the usage of different DTMs, results obtained using a 90 m resolution SRTM DTM and a 0.5 m resolution DTM were compared. The latter DTM was derived by an airborne LiDAR (Light Detection And Ranging) carried out in 2009. The reason for selecting SRTM is that it is a freely available online product that could virtually be available for any location in which a GB-InSAR might be installed. To perform comparison, the SRTM DTM was over-sampled to a pixel size of 5 m through the Kriging algorithm, so that the cell size was similar to GB-InSAR image pixels and the resulting DTM was not too much degraded. The LiDAR DTM was under sampled to a pixel size of 2 m, which is similar to the average pixel size of the radar scene in Valoria. The LoS displacement maps resulting from projection over the two DTMs are compared in Figure 15. No significant differences in the spatial distribution of movements can be perceived, meaning that once the geo-referencing process is accomplished with sufficient accuracy with respect to the expected movement rates, the use of the SRTM DTM or of a more accurate DTM provides comparable displacement maps if the morphology of the area is quite regular, as it was in Valoria.

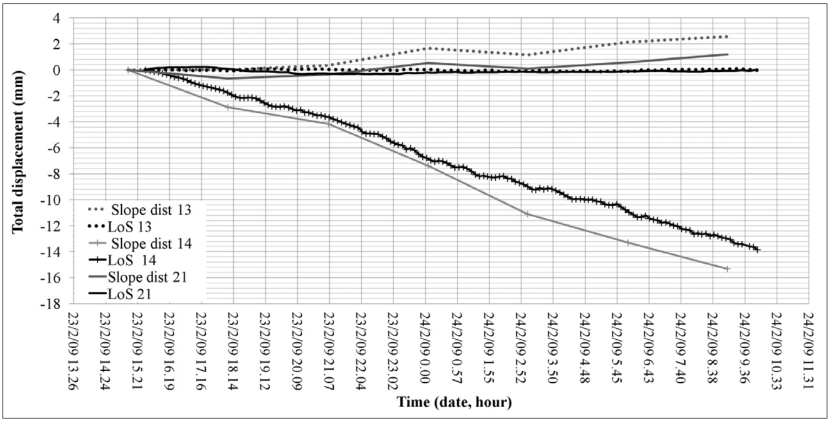

Figure 14 - Comparison between ATS and GB-InSAR results: slope distances of prisms 13, 14 and 21 (23-24 Feb. 2009) and LoS displacement of the corresponding permanent scatterers.

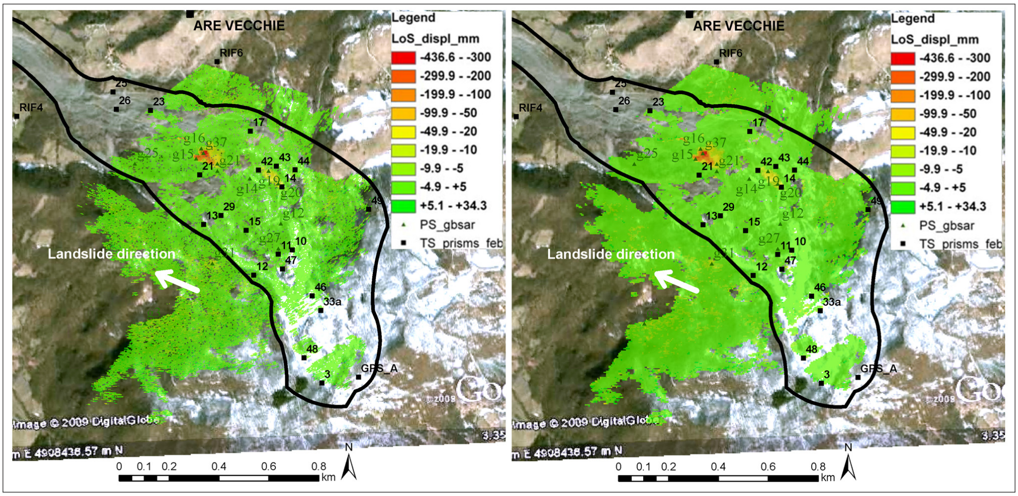

Figure 15 - GB-InSAR LoS displacement maps: evaluating the importance of the DTM for a good re-projection. On the left the re-projection based on the airborne LiDAR DTM; on the right the re-projection based on SRTM DTM. The black line shows the landslide boundaries.

Conclusions

The use of advanced technologies for remotely monitor surface movements can improve knowledge of the evolution of landslide phenomena. In addition, the integration of various techniques in order to implement early warning systems that can monitor the evolution of landslides in near real-time is becoming more and more technologically and economically accessible. The reliability of results and the integration of results in a common reference framework within a GIS play a key role when public administrations have to use monitoring networks to plan actions in case of emergency. In this research, some major critical aspects to consider for implementing a reliable monitoring system integrating GNSS, ATS and GB-InSAR were analysed and discussed with reference to the Valoria landslide monitoring network setup and results.

Results show that controlling the stability of ATS pillar and of reference prisms by means of GNSS surveys is important in order to check for the accuracy of the results of an ATS monitoring system. Periodic GNSS control of the ATS pillar and the adoption of bi-axial tiltmeter to compute pillar displacements was an efficient solution for confirming the invariant position of the ATS. Results also showed that in case of landslide movements larger than a few cm, simplified “monitoring” corrections of the atmospheric errors associated to ATS measurements can be considered adequate, provided that the reference prisms are proved to be stable over time. For that purpose the use of prisms mounting solutions that allow the co-axial installation of prisms and GNSS receivers to check for reference prisms stability proved to be of great help. Periodic GNSS surveys of ATS and reference prisms proved also necessary for performing a correct reference framework transformation of ATS monitoring results from a local coordinate system to the ETRF2000 global system. On the other hand, geo-referencing of GB-InSAR displacement maps was successfully achieved by performing GNSS survey of the radar position, by measuring LoS direction by a simple compass and by projecting data over DTMs of different resolution. Actually, results showed that due to the characteristics of GB-InSAR surveys, and the dm/day rate of movement in Valoria, no significant difference in the spatial distribution of geo-referenced LoS displacement data was generated by projecting data on a low-resolution DTM (such as the SRTM) or on a high resolution DTM (such as these obtained by an airborne LiDAR). This proved that integrated monitoring results from GNSS, ATS and GB-InSAR can effectively be integrated in a GIS by using freely available databases of satellite products, such as SRTM DTMs or high resolution images available via Google Earth. These products are available for many locations around the globe, and certainly for the whole Italian territory, and they represent a valuable resource for public administrations and authorities that have to manage natural hazards by means of integrated monitoring networks.

Acknowledgements

Colleagues F. Ronchetti, A. Daehne, F. Bonacini are acknowledged for collaboration in carrying out ATS and GNSS surveys. P. Farina L. Mayer, A. Cerutti and P. Ricci of IDS (Ingengeria Dei Sistemi, Pisa, Italy) are acknowledged for collaboration in GB-InSAR monitoring. The research was carried in collaboration with Emilia Romagna Region (Po river affluent office of Modena and Agency for Civil Protection) in the frame of the following national relevance research projects (PRIN - Progetti di Ricerca di Interesse Nazionale): Multi-temporal Analysis and Surveying in the Framework of a Geo-Spatial

Information System for the control of movement and deformation of Environmental Risk Areas (responsible A. Capra); WISELAND - Integrated Airborne and Wireless Sensor Network systems for Landslide Monitoring (responsible A. Corsini).

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Received 31/01/2012, accepted 24/09/2012