High resolution satellite multi-temporal interferometry for detecting and monitoring landslide and subsidence hazards

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Abstract

With the increasing number of radar satellites and improved data processing tools, multi-temporal interferometry (MTI) can considerably enhance our capabilities of monitoring landslide and subsidence hazards. MTI provides long-term (years), regular (weekly-monthly), precise (mm) measurements of ground displacements over large areas (thousands of km^2), combined with high spatial resolution (up to 1-3 m) and possibility of multi-scale (regional to site-specific) investigations using the same series of radar images. To highlight the great potential of high resolution MTI we discuss application examples from two seismically active regions prone to land instability: i) Albania, including the large plain area occupied by the city of Tirana and nearby scarcely populated mountains, and ii) Haiti, including the Port-au-Prince metropolitan area, with coastal and mountain zones destabilized by the 2010 Mw 7.0 earthquake. It is shown that MTI can provide very useful results in a wide range of geomorphic, climatic and vegetation environments.

Keywords: landslide, subsidence, hazard, detection, monitoring, satellite interferometry

1. Introduction

In situ investigations and monitoring of areas prone to landslide or subsidence are expensive, typically conducted only after the ground failure, and limited in terms of spatial and temporal coverage. Therefore, the use of complementary, cost-effective or economically sustainable approaches to hazard detection and assessment is an important issue.

Different remote sensing techniques can be used to measure ground surface displacements linked to land instability (e.g., Bally, 2014). These include ground-based radar interferometry (e.g., Lowry et al., 2013), air-borne and terrestrial LiDAR (e.g., Monserrat and Crosetto, 2008; Jaboyedoff et al., 2012), air- and space-borne image matching (e.g., Kääb, 2002; Raucoules et al., 2013).

In this work we solicit a widespread application of advanced satellite MTI, with emphasis on early detection of ground displacements via long-term (years) monitoring. MTI approach is cost-effective and can deliver large quantities of useful information for scientists and land-use managers involved in landslide and subsidence hazards mitigation.

In particular, satellite MTI offers outstanding surveying capability of land instability (e.g., Hooper et al., 2012; Bally, 2014; Tomás et al., 2014; Wasowski and Bovenga 2014a,b). The users of MTI can rely on the unique strengths of the technique:

a. Large area coverage (thousands of km^2) together with high spatial resolution (1-3 m) of the new radar sensors e.g., COSMOSky-Med, TerraSAR-X (Table 1) and multi-scale investigation option (regional to site-specific);
b. Very high precision (mm-cm) of surface displacement measurements only marginally influenced by bad weather;
c. Regular, high frequency (days-weeks) of measurements over long periods (years);
d. Retrospective studies using long-period (>20 years) archived radar imagery.

Here we illustrate the great potential of high resolution MTI for the detection and monitoring of landslide and subsidence hazards by presenting application examples from two areas located in different geomorphic, climatic and vegetation settings: Central Albania (Tirana County plain and mountains) and Haiti (coastal and mountain regions).

Table 1 Selected characteristics of principal Synthetic Aperture Radar (SAR) sensors; future missions shown in grey (updated after Wasowski and Bovenga, 2014a)

Satellite mission	Wave-length (cm)	Life status	Resolution Az./Range (m)	Repeat Cycle (days)	Swath width (km)	Max. Vel. (cm/yr)	Incident Angle (degree)
C-band							
ERS-1/2	5.6	1992÷2001	≈ 6 / 24	35	100	14.6	23
ENVISAT	5.6	2003÷2010	≈ 6 / 24	35	100	14.6	19÷44
RADARSAT-1	5.5	1995÷	≈ 8÷30	24	45 (fine) 100 (Strip) 200 (Scan)	20.4	20÷50
RADARSAT-2	5.5	2007÷	≈ 3 / 3 ≈ 8 / 8 ≈ 26 / 25	24	10 (Spot) 40 (Strip) 200 (Scan)	20.4	20÷50
Sentinel-1	5.6	2014-2024	20÷5	6, 12	250	85	30÷46
RADARSAT Constellation Mission (3 Sat)	5.5	2018-2026	5÷50	3, 12	30÷350	163,2	20÷55
L-band							
J-ERS	23.5	1992÷1998	18	44	75	48.7	35
ALOS PALSAR	23.6	2006÷2011	≈ 5 / 7÷88	46	40÷70	46.8	8÷60
ALOS PALSAR-2	22.9	2014÷2019	1/3 3÷10/3÷10 100/100	14	25 (Spot) 50÷70(Strip) 350 (Scan)	149.2	8÷70
SAOCOM (2 Sat)	23.5	2015÷2021	10÷50	8, 16	20÷150	268	20÷50
X-band							
COSMO-SkyMed (4 Sat)	3.1	2007÷2014	≈ 2.5 / 2.5 1.0 / 1.0	2,4,8,16	10 (Spot) 40 (Strip) 200 (Scan)	17.7 35.4 70.7 141.4	20÷60
TerraSAR-X	3.1	2007÷2018	≈ 3.3 / 2.8 1.0 / 1.0	11	10 (Spot) 30 (Strip) 100 (Scan)	25.7	20÷55
KOMPSAT-5	3.2	2013-2018	3 / 3 1 / 1	28	5 (Spot) 30 (Strip)	10.4	20÷45
COSMO-SkyMed-2 (2 Sat)	3.1	2016	1÷3		10÷40		
TerraSAR-X-NG	3.1	2015	0.25÷30	11 (constel. with PAZ)	5÷20 (Spot) 10÷24 (Strip) 50÷400 (TOPS)		20÷50

2. Background information on MTI

MTI is based on processing of long temporal series of synthetic aperture radar (SAR) images (typically >15) to remove the atmospheric disturbance, and on the selection of radar targets on the ground that provide a backscattered phase signal coherent in time (e.g., Hooper et al., 2012). The majority of radar targets correspond to human-made objects (e.g., buildings and other engineered structures), as well as to rock outcrops and bare ground. To make distance measurements between the satellite sensor and the target, phase difference images (interferograms) are generated using radar images acquired for the study area during successive satellite passes. Detailed information on applied satellite interferometry and MTI is available in review articles published in the engineering geology literature (e.g., Colesanti and Wasowski, 2006; Wasowski and Bovenga, 2014a and references therein).

An important limitation of MTI is that the displacements are measured in one dimension along satellite slant range or Line of Sight (LOS), with incidence angles varying between about 20°-50° (Table 1), and it is nearly impossible to retrieve movements in the radar satellite flight direction (azimuth), i.e., approximately north-south (Fig. 1). In addition, it is very difficult to measure high velocity displacements e.g., exceeding few tens of cm/year (Table 1) and strong non-linear deformations. For a detailed discussion of MTI technical limitations and data interpretation issues, as well as guidelines on how these can be mitigated, the reader is referred to a recent article by Wasowski and Bovenga (2014a).

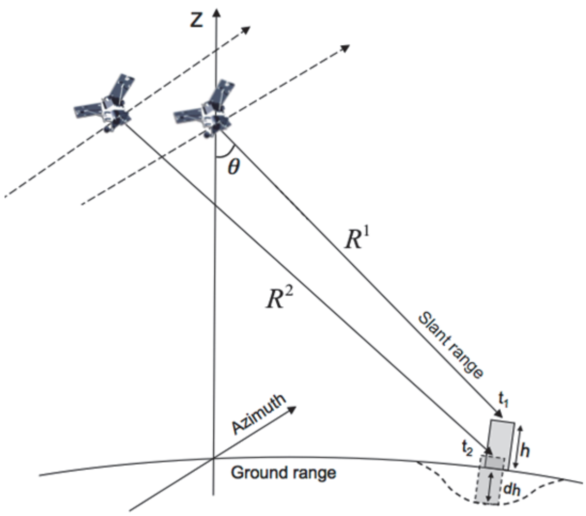

Fig. 1 Two radar acquisitions during successive satellite passes: R = sensor-target geometrical distance, h = target elevation, dh = target displacement, and θ = incidence angle (modified after Wasowski and Bovenga, 2014a).

The standard MTI products include: i) geo-located radar targets; ii) map or optical image with overlaid average annual displacement velocities of targets; iii) displacement time series of each target. In recent years Google Earth™ tools and associated optical imagery are being increasingly used to display distribution and movement rates of radar targets (cf. Bovenga et al., 2012).

3. Satellite data and MTI processing

3.1 Radar data

In this study we used two stacks of high resolution (3 m) COSMO-SkyMed (CSK) radar images. For Albania we had 39 CSK images covering the period May 2011 - June 2014. For Haiti we obtained about 100 CSK images covering the period June 2011 – August 2013. Technical specifications of CSK sensor are given in Table 1.

3.2 MTI processing

Our results are based on the application of the SPINUA (Stable Point INterferometry over Unurbanized Areas) MTI algorithm. This Persistent Scatterers Interferometry-like algorithm, originally developed for detection and monitoring of radar targets in non- or scarcely-urbanized areas (Bovenga et al., 2005), has been updated in order to increase its flexibility also for the applications in densely urbanized areas, as well as to guarantee proper processing of high-resolution X-band data from the new generation radar sensors such as CSK (Bovenga et al., 2012).

The quality of SPINUA processing has been confirmed in many applications in the last several years. In particular, the results obtained through SPINUA have been cross-compared with those derived by using other MTI techniques (Wasowski et al., 2007; Wasowski and Bovenga, 2014a), and validated by using in situ measurements from both GPS/GNSS and leveling (Bovenga et al., 2013).

4. MTI application example from Albania

4.1 Environmental setting

The area of interest is in the central region of Albania, a country that lies in the western part of the Balkan Peninsula on the eastern coast of the Adriatic Sea (Fig. 2). Albania belongs to the Dinarides (the southern extension of the Alpine belt) and its territory is predominantly mountainous and hilly. The coastal lowlands to the west and intermountain plains representing less than 25% of the land (Meco and Aliaj, 2000).

Regarding the geological setting, the study area can be divided into the western part (lowland), which belongs to the Periadriatic Foredeep Basin, and the “External Albanides” (mountains) to the east (Fig. 2).

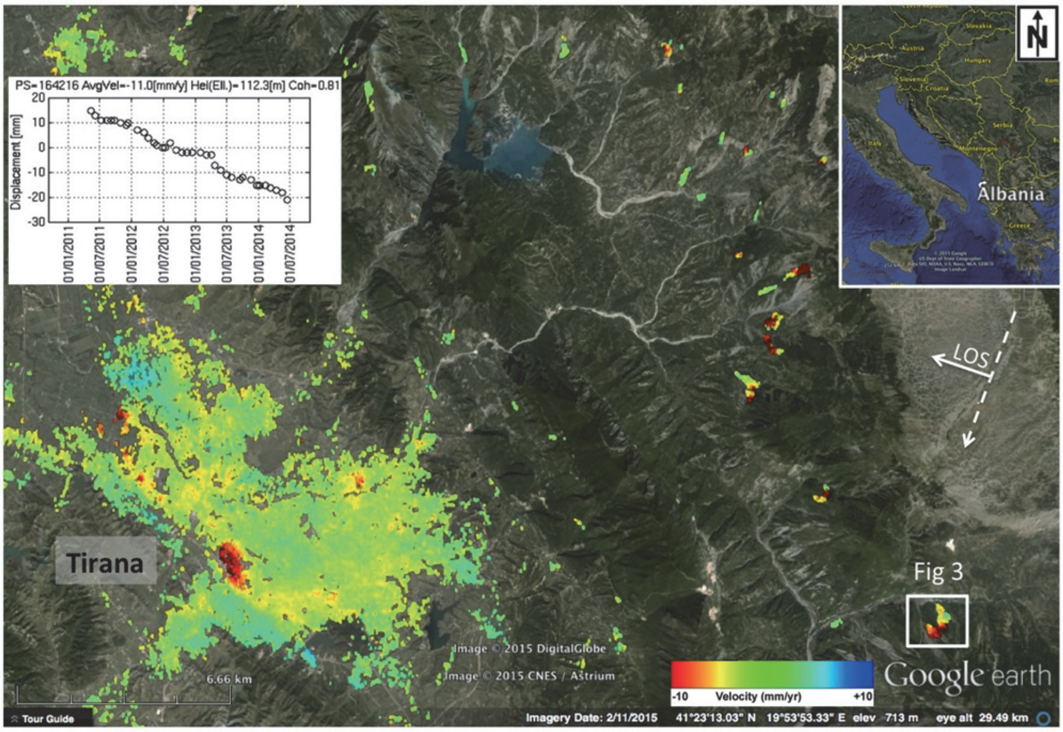

Fig. 2 Line of sight (LOS) velocity of radar targets (color dots) in Central Albania (cf. inset figure), including the plain of Tirana and the mountains to NE; velocity scale saturated to ±10 mm/year. Reddish to yellowish targets move away from the satellite and denote subsidence in Tirana (cf. inset graph with displacement time series of a target from SW part of the city) and slope movements in the mountains. White rectangle indicates unstable slope shown in Fig. 3. The background image is from Google Earth™.

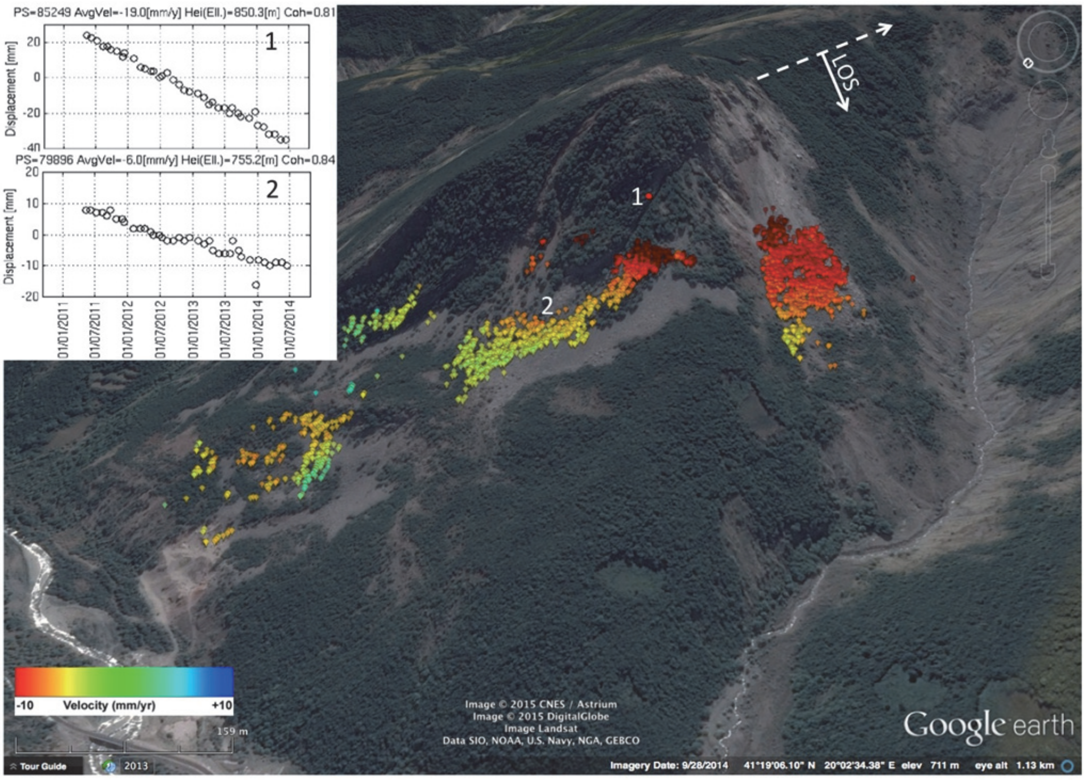

Fig. 3 Unstable slope detected in the mountain range east of Tirana. Reddish to yellowish dots (radar targets) indicate landslide activity and slope deformations and/or instability of slope debris; velocity scale saturated to ±10 mm/year. Inset graphs show displacement time series of two representative targets.

The Foredeep includes Miocene and Pliocene molasse and Quaternary (mainly alluvial) sediments, while flysch sequences and carbonates represent the two predominant lithologies in the mountain range (Meço and Aliaj, 2000).

Albania belongs to one of the most seismically active regions of Europe – the Western Balkans. At present, the lowlands and coastal regions of western Albania are characterized by active thrust faulting, while active extension on normal faults occurs in the mountains in the east of the country (Meço and Aliaj, 2000).

Albania belongs to the Mediterranean climatic zone characterized by hot and dry summers, but the average annual rainfall is high and extremely variable, from about 700-800 mm in the SE coastal areas to about 3000 mm in the mountains in the NE part of the country (Meço and Aliaj, 2000). Winter represents the most rainy season of the year, with snow precipitation common in the interior mountains.

4.2 Regional scale detection of land instability

Figure 2 provides a wide-area overview of MTI results for the Central Albania region. The SW portion of the study area is marked by a high density cluster of radar targets corresponding to the metropolitan area of Tirana (about 40 km^2). Although a general stability of the capital city territory is apparent, there are several groups of moving radar targets, which indicate a more or less localized ground displacements. The movements are away from the satellite sensor (downward) and denote the occurrence of subsidence phenomena. The average rate of deformation is low, only seldom exceeding 10 mm/year (cf. displacement time series in Fig. 2).

Although detailed geological data are not available at present, it is apparent that some of the unstable sites detected in Tirana can be linked to ground settlement processes occurring in the newly developed (last 10 years) areas of the city. The presence of semi-linear deformation trends (Fig. 2) and the location of the unstable sites on flat ground near the river network suggests that settlements are induced by gradual loading of alluvial (compressible) sediments by the new engineering constructions (mainly houses).

The origin of some subsiding areas could also be related to the increased ground water withdrawal in Tirana. Indeed, in recent years the city has not only experienced huge urban expansion into the new areas (with the construction of formal and informal housing), but the population in the Tirana area has more than doubled from about 250,000 inhabitants in 1991 to 600,000 in 2008 (World Bank, 2013).

The high density of radar targets (over 1000/km^2) in the Tirana region is in sharp contrast with the relative scarcity of targets in the mountainous area to the NE and E of the city (Figure 2). This can be related to the presence of dense vegetation (trees), very limited number of human-made objects (e.g. houses) that can act as coherent targets, and the snow cover in winter period in the Albanian mountains.

Nevertheless, the radar data processing provided useful results even in such a harsh mountainous environment for MTI applications. In particular, we identified over 10 clusters of moving targets, which, as illustrated below, are indicative of landslide activity or slope instability.

4.3 Local scale landslide monitoring

We found no information in the English literature about slope failures in the mountains ENE of Tirana. However, active erosion and landslides can be easily recognized on high resolution Google Earth™ imagery (Fig. 2).

Signs of active landsliding are evident in Fig. 3, which also shows the distribution and average annual velocity of radar targets. The measured velocities are very low, from few to about 20 mm/year (cf. representative displacement time series in Fig. 3). One group of moving targets coincides with the upper part of a landslide body, which deflected the local stream; thus the very slow target motion reflects the post-failure activity of the slide. The displacements of other groups of targets may indicate the movements of slope debris and/or incipient slope deformations. Clearly, in situ inspection would be helpful in this case.

5. MTI application example from Haiti

5.1 Background information

The example of Haiti is of interest, because high resolution X-band MTI applications are rare in tropical regions (Wasowski and Bovenga, 2014b). This stems from the difficulty of obtaining good MTI results in areas with dense and rapidly growing vegetation.

Haiti occupies the western part of the island of Hispaniola located in the Caribbean Sea (Fig. 4). It has mostly humid tropical climate with high temperatures throughout the year and two rainy seasons: April–June and August-October (see http://www.britannica.com/EBchecked/topic/251961/Haiti/54458/Climate).

The vegetation cover is typically dense with the exception of the intensely urbanized areas like that of Port-au-Prince, the capital city of Haiti (Fig. 4). Also the mountainous regions are much vegetated (Fig. 5).

The study area covers a large plain and coastal zones (including the metropolitan region of Port-au-Prince) and the mountains bordering the plain to the NW and SE (Fig. 4). While Miocene-Paleocene age rocks predominate in the mountains, the plain contains abundant Quaternary and Pliocene alluvial deposits (Lambert et al., 1987).

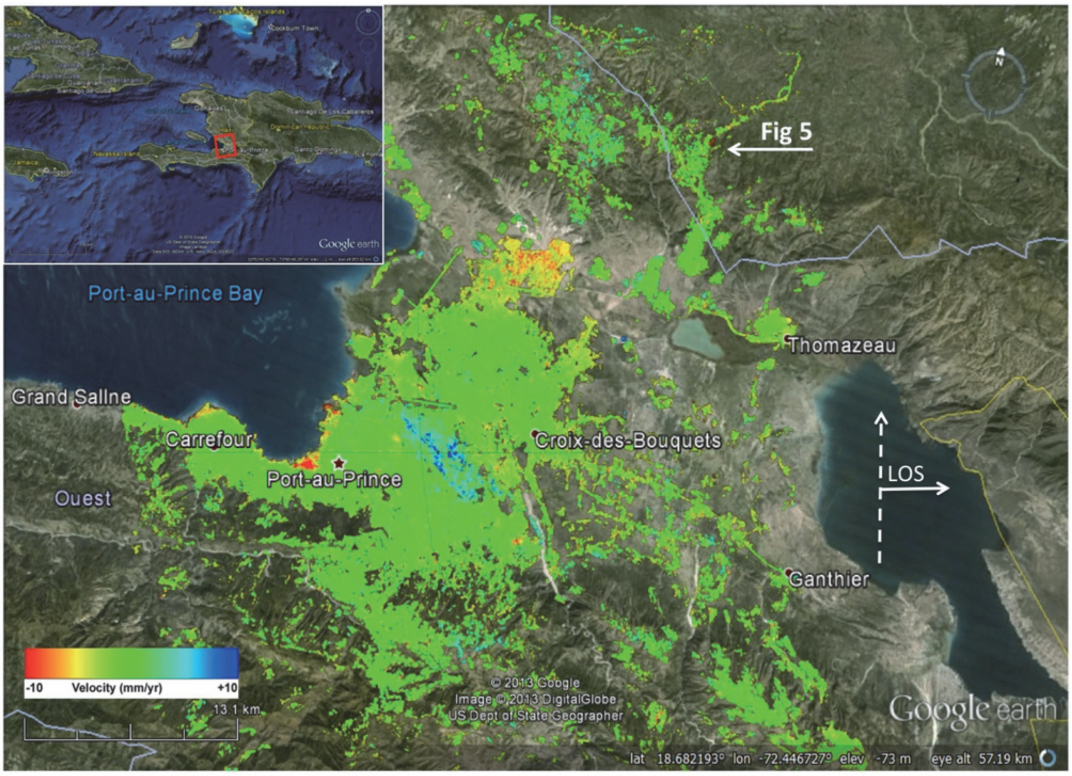

Fig. 4 Line of sight (LOS) velocity of radar targets (color dots) in the metropolitan area of Port-au-Prince, Haiti, and the surrounding regions (red rectangle in inset figure indicates coverage of satellite imagery); velocity scale saturated to ±10 mm/year. Reddish to yellowish dots represent targets moving away from the satellite sensor and denote significant (up to few cm/year) subsidence affecting coastal areas. White arrow indicates location of landslide shown in Fig 5. The background image is from Google Earth^{TM}.

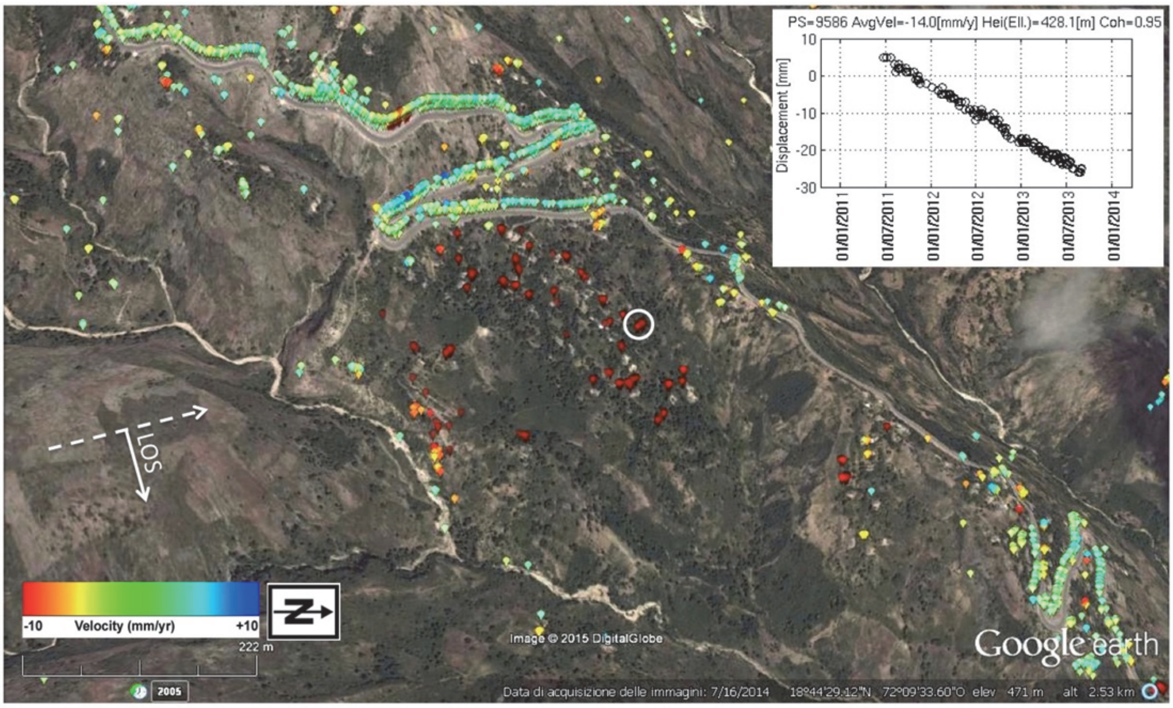

Fig. 5 Deep-seated landslide (center of image) and local instabilities along National Route N°3 of Haiti. Clusters of reddish to yellowish radar targets indicate the landslide motion and localized instabilities affecting the slope and road embankments; velocity scale saturated to ±10 mm/year. White circle marks position of landslide target whose displacement time series is shown in inset graph.

5.2 Regional scale detection of land instability

Figure 4 provides a wide-area overview of MTI results for the large plain and coastal zones occupied by the Greater Port-au-Prince area and the city of Carrefour, and for the nearby mountains. Overall, the amount of available information is impressive, with over two and a half million measurement points and their average density exceeding 1700/km^2. However, the distributions of radar targets in the lowland and mountain regions are different, because of the sharp differences in the density of urbanization and vegetation cover.

In particular, the extremely high density of radar targets in the metropolitan area of the Haitian capital (on the order of 10,000/km^2) allowed the detection and detailed spatial delimitation of subsidence processes affecting river deltas and coastal areas of the Port-au-Prince and Carrefour region (Fig. 4). The over two year long time series of radar target displacements showed that the subsidence movements locally exceed few cm/year (Nutricato et al., 2013).

In the mountains, away from large urban centers, the amount of obtained MTI information was lower and spatially variable. Nevertheless, thanks to the high resolution of CSK radar imagery and the presence of human-made structures dispersed in vegetated terrain (Fig. 5), the density of targets in many rural areas resulted suitable for slope instability detection. Note that some areally limited clusters of moving radar targets are not visible in Fig. 4, because its scale is too small.

5.3 Local scale landslide monitoring

Figure 5 shows an example of a landslide and localized instabilities detected from MTI results. The slide is about 300 m long and 200 m wide and has its toe eroded by an ephemeral stream. The slope cuts along the National Route N°3 passing around the unstable area expose stratified sandstones and limestones. The site is located in the Montagnes du Trou D'Eau, a moderate elevation range distant few tens of kilometers from Port-au-Prince.

No information is available on the origin of the main failure, but the examination of "historical" optical images in Google Earth^{TM} shows that the Triano landslide predates the 2010 7Mw Haiti earthquake. The slide could be quite old (decades or more) considering the subdued geomorphic expression, dense vegetation cover and the presence of small human dwellings. The latter belong to the village of Triano and, together with the adjacent road, are the sources of radar targets identified on the landslide and in its surroundings.

The LOS velocities of the radar targets on the slide are similar, averaging around 15 mm/year (Fig. 5). This together with the overall geomorphic expression of the failed slope are indicative of a deep creeping landslide movement. Significantly, the displacement rates of targets on the slide are significantly greater than those of other nearby moving targets. The latter move at velocities typically below 10 mm/year. In situ checks indicated that these moving targets denote localized instabilities affecting the slope, road embankment (including gabions) and isolated human-made structures (Fig. 5).

The above example demonstrates the capability of high resolution (3 m) MTI to provide site-specific information on landslide activity even in vegetated settings. It is also evident that with such resolution radar imagery one can also use MTI to monitor stability of roads in landslide prone areas.

6. Concluding discussion

Land instability hazards related to landslide and subsidence processes affect most countries in the world and represent a global problem. This and the continuous growth of the world population, with urbanization of areas susceptible to failure, combined with the increasing climate variability, imply greater vulnerability and risk.

However, extensive in situ monitoring efforts are in most situations unaffordable. The recent literature on satellite interferometry applied to engineering geology problems (e.g., Cigna et al., 2014; Tomás et al, 2014; Wasowski and Bovenga, 2014a,b and references therein), as well as the case studies presented in this work, show that thanks to the wide-area coverage of satellite imagery (tens of thousands of km^2) MTI represents a cost-effective monitoring technique. When combined with a high spatial resolution (1-3 m) and improved re-visit frequency (days-weeks) of the new radar sensors (Table 1), the millimeter precision MTI surveying can provide enormous amounts of high quality information about ground surface displacements occurring in areas susceptible to slope or subsidence hazards.

Finally, we expect that with regular globe-scale coverage and freely available imagery, new radar satellite background missions such as the European Space Agency's Sentinel-1 will foster an even wider and more efficient use of MTI in ground hazard investigations.

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