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The Use of High Resolution Satellite MTI for Detecting and Monitoring Landslide and Subsidence Hazards in Tirana

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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 km2), 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 an application example from seismically active regions prone to land instability in Albania, including the large plain area occupied by the city of Tirana and nearby scarcely populated mountains. 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 [1]. These include ground-based radar interferometry [12], air-borne and terrestrial LiDAR [10, 8], air- and space-borne image matching [9, 11].

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 [1, 7, 14, 15, 16]. The users of MTI can rely on the unique strengths of the technique:

- Large area coverage (thousands of km2) 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);
- Very high precision (mm-cm) of surface displacement measurements only marginally influenced by bad weather;
- Regular, high frequency (days-weeks) of measurements over long periods (years);
- 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 example from Central Albania (Tirana County plain and mountains).

Table1. *Selected characteristics of principal Synthetic Aperture Radar (SAR) sensors; future missions shown in grey* [*15*].

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 [7]. 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 [6, 15].

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 [15].

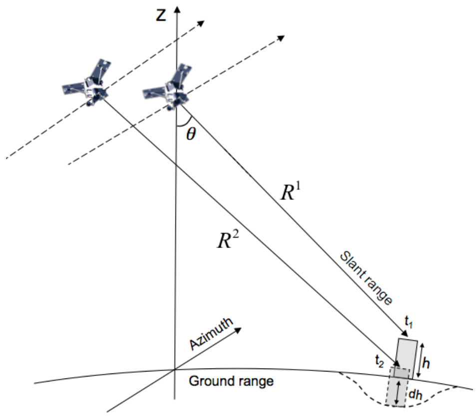

Fig1. *Two radar acquisitions during successive satellite passes: R = sensor-target geometrical distance, h = target elevation,* d_h *= target displacement, and* θ *= incidence angle* [15].

The standard MTI products include: 1) geo-located radar targets; 2) map or optical image with overlaid average annual displacement velocities of targets; 3) displacement time series of each target. In recent years Google EarthTM tools and associated optical imagery are being increasingly used to display distribution and movement rates of radar targets [3].

3. Satellite Data and MTI Processing

3.1. Radar Data

In this study, we used one stack of high-resolution (3 m) COSMO-SkyMed (CSK) radar images. We had 39 CSK images covering the period May 2011 - June 2014. Technical specifications of CSK sensor are given in Table 1.

3.2. MTI Processing

Our results 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 [2], 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 [3].

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 [15, 17], and validated by using in situ measurements from both GPS/GNSS and leveling [4].

4. MTI Application

4.1. Environmental Settings

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 [13].

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

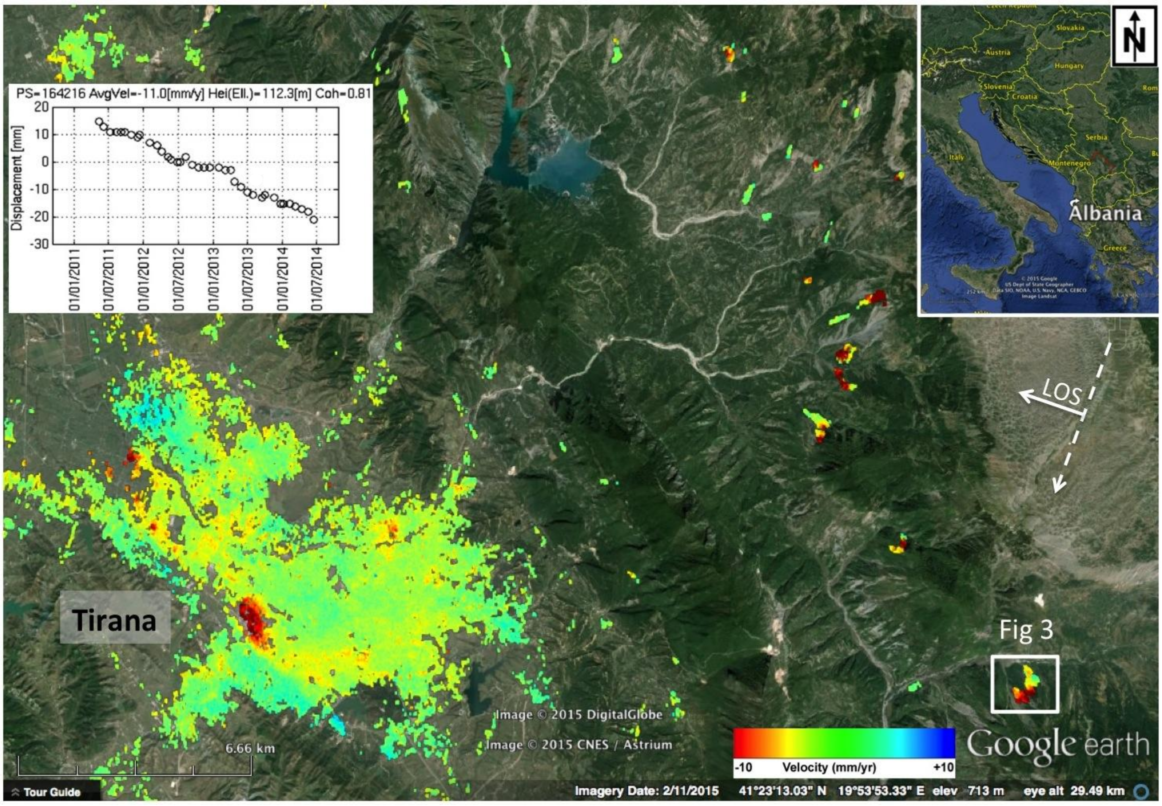

Fig2. *Line of sight (LOS) velocity of radar targets (color dots) in Central Albania (cf. inset figure), including the plain of Tirana and the mountains to NE; velocity scale saturated to ±10 mm/year. Reddish to yellowish targets move away from the satellite and denote subsidence in Tirana and slope movements in the mountains. White rectangle indicates unstable slope shown in Fig. 3. The background image is from Google Earth™.*

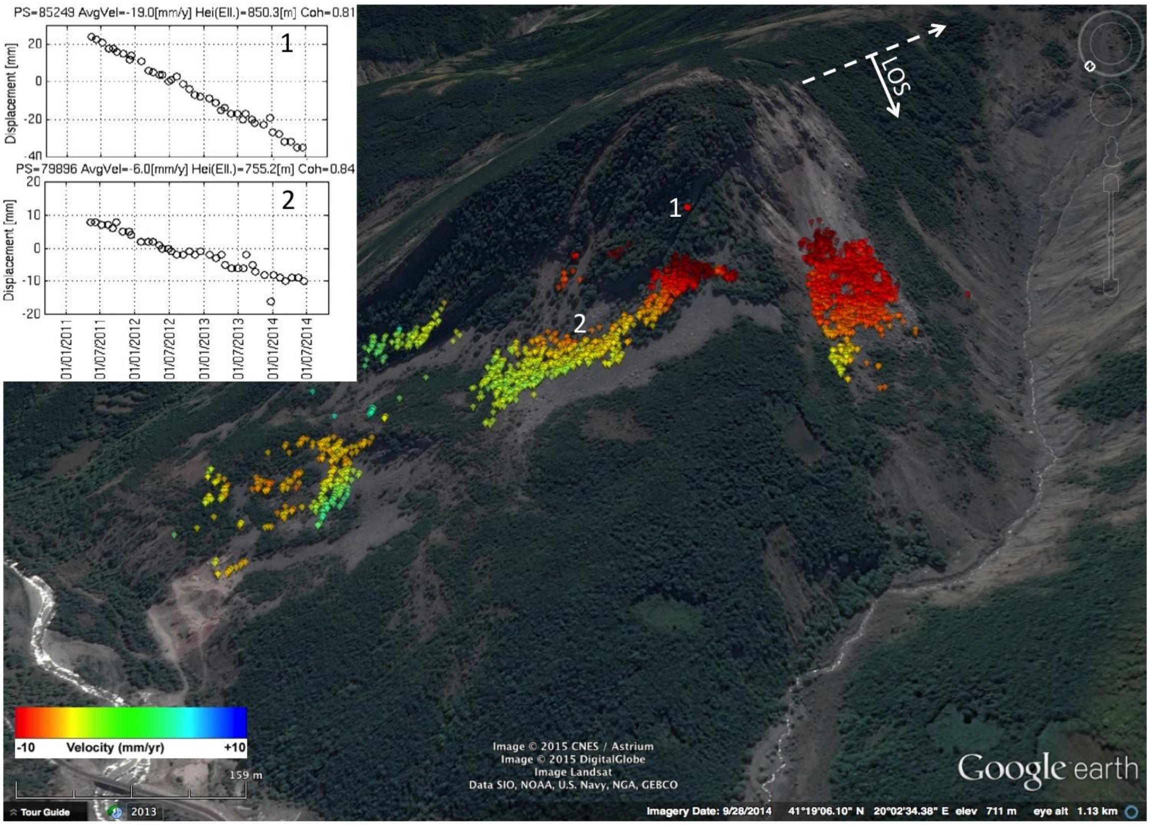

Fig3. *Unstable slope detected in the mountain range east of Tirana. Reddish to yellowish dots (radar targets) indicate landslide activity and slope deformations and/or instability of slope debris; velocity scale saturated to ±10 mm/year. Inset graphs show displacement time series of two representative 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 [13].

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 [13].

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 [13]. Winter represents the rainiest 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 km2). 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/km2) 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.

5. Concluding Discussion

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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 study presented in this work, show that thanks to the wide-area coverage of satellite imagery (tens of thousands of km2) 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.

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