# High resolution satellite SAR multi-temporal interferometry for regional scale detection of landslide and subsidence hazards

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*Abstract*—**Among a number of advanced satellite-based remote sensing techniques, synthetic aperture radar (SAR) multi-temporal interferometry (MTI) appears the most promising for fostering new opportunities in landslide and subsidence hazards detection and assessment. MTI is attractive to those concerned with terrain instability hazards because it can provide very precise quantitative information on slow displacements of the ground surface over huge areas with limited vegetation cover. Although MTI is a mature technique, we are only beginning to realize the benefits of the high-resolution imagery that is currently acquired by the new generation radar satellites (e.g., COSMO-SkyMed, TerraSAR-X). In this work we demonstrate the great potential of high resolution MTI for regular, wide-area detection of ground instability hazards by presenting results from two regions characterized by different geomorphic, climatic and vegetation conditions: densely populated metropolitan area of Port-au-Prince (Haiti), with the coastal areas and local slopes destabilized by the 2010 Mw 7.0 earthquake, and the remote high mountain region of Southern Gansu Province (China) prone to large slope failures. The interpretation and widespread exploitation of high spatio-temporal resolution MTI results can be facilitated by visualizing the scientific data using Google Earth™ tools or other web-based applications.**

## I. INTRODUCTION

Ground instability hazards caused by landslides and subsidence can affect any country in the world and as such constitute a global problem. This and the growth of population, with urbanization of areas susceptible to ground failure, together with the climate change, call for the development of effective and more economically sustainable approaches to hazard assessment and reduction. We argue that the extensive exploitation of modern remote sensing technologies, with focus on early detection of small pre-failure ground deformations through long-term monitoring, represents one of the emerging options for scientists concerned with slope and subsidence hazards.

In particular, among different innovative remote sensing techniques capable of detecting and monitoring ground surface changes and deformations related to terrain instability e.g., air/terrestrial LiDAR [1], [2], or air/space-borne image matching [3], [4], the satellite MTI offers excellent surveying capabilities e.g., [5], [6], [7], [8]. The applications of MTI can rely on the following strengths of the technique:

- Wide-area coverage (tens of thousands of $km^2$) combined with high spatial resolution (up to 1 m for the new generation radar sensors such as COSMO-SkyMed and TerraSAR-X), and the possibility of conducting multi-scale investigations (from regional to site-specific);
- Systematic, high frequency (from few days to weeks) measurements over long periods (years);
- High precision of surface displacement measurements (mm-cm resolution) only little affected by bad weather conditions;
- Integration of monitoring based on new satellite imagery with retrospective studies (using archived imagery) to

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investigate ground failure history and long-term (years-decades) instability processes;

- Regional scale, regular update on ground stability conditions in inhabited areas or those to be urbanized (prevention and land use planning).

In this work we illustrate what kind of geospatial information relevant for ground instability hazard assessment the MTI technique can provide. This is done by considering regional-scale applications in two settings characterized by different geomorphic, climatic and vegetation conditions:

1) The densely populated metropolitan area of Port-au-Prince (Haiti), with the coastal areas and local slopes destabilized by the 2010 Mw 7.0 earthquake;
2) The remote mountain region of Southern Gansu Province (China) prone to large slope failures.

Even though MTI applications are considered cost-effective e.g., [7], [9], their potential is relatively less exploited in the geomorphologist community with respect to other innovative surveying techniques (e.g., LiDAR). This, and the capability of MTI to provide high quality geo-referenced information for process-based modeling of terrain instability hazards, further motivates our work.

## II. BACKGROUND INFORMATION ON MTI

MTI techniques rely on processing of long temporal series of radar images (usually >15) to remove the atmospheric disturbance, and on the identification of radar targets on the ground (mainly human-made structures, rock outcrops) that provide a backscattered phase signal coherent in time (e.g., [5], [7]). To perform distance measurements between the satellite sensor and the target, phase difference images (interferograms) are generated by using radar images acquired over the same area during successive satellite passes. For more details on space-borne interferometry and MTI the reader is referred to the above cited articles and the vast literature on radar remote sensing.

Regarding practical applications, the standard products of MTI include: i) position of radar target (lat., long., height); ii) map showing average annual displacement rates of targets; iii) displacement time series of each target.

One significant limitation of MTI is that it is usually impossible to detect strong non-linear deformations and high velocity displacements (e.g. exceeding few tens of cm/year). Furthermore, the displacements are measured in one dimension along satellite Line of Sight (LOS), with incidence angles varying between about 20°-50°, and it is nearly impossible to retrieve movements in the radar satellite flight direction (azimuth), i.e. approximately north-south.

## III. EXAMPLES OF HIGH RESOLUTION WIDE-AREA MTI APPLICATIONS TO GROUND INSTABILITY DETECTION

The two examples of regional scale MTI applications rely on processing of high resolution (3 m) X-band imagery acquired by the Italian constellation of radar satellites COSMO-SkyMed (CSK). In both cases the results were obtained by using the updated version of the SPINUA MTI algorithm [10]. The obtained results were ground checked. The quality and validation of SPINUA products is further discussed in [7].

### A. *Example of MTI application to coastal subsidence hazards in Port-au-Prince, Haiti*

The example of Haiti is of interest, because it shows that MTI can furnish very useful data on terrain instability even in case of tropical regions characterized by dense and rapidly growing vegetation, as well as by significant climatic variability (two rainy seasons) with intense precipitation events. Regions with such environmental characteristics can be harsh for MTI applications, because of the coherence loss problems that can occur especially when exploiting shorter wavelength (X- and C-band) radar data.

Despite the unfavorable setting, MTI processing of over 100 high resolution (3 m) CSK mages (June 2011 - August 2013) led to the identification of a large number of radar targets (nearly 2,997,000), with full CSK frame (~1700 km$^2$ coverage) density exceeding 1700 radar targets/km$^2$ [11]. Thanks to the high resolution of CSK radar imagery and the presence of many human-made structures dispersed in heavily vegetated terrain, even some landslide prone rural areas had a density of targets suitable for ground deformation detection [8], [11].

Importantly, the extremely high density of radar targets in the metropolitan area of the Haitian capital (on the order of 10,000/km$^2$) resulted in the detection and clear spatial delimitation of significant subsidence phenomena affecting river deltas and coastal areas of the Port-au-Prince and Carrefour region (Fig. 1). The over two year long time series of radar target displacements show that the maximum rate of subsidence movements locally exceed few cm/yr. This implies increasing flooding (or tsunami) hazard, as well as risk, considering high population density in coastal areas.

### B. *Example of MTI application to slope hazards in mountains of Southern Gansu, China*

This region, known to be affected by large magnitude (M7-8) earthquakes and catastrophic landslides, is characterized by steep slopes with elevations reaching 4000 m (Fig. 2). Vegetation cover is limited and rocks include Silurian and Carboniferous slates and phyllites, as well as Permian and Devonian metamorphosed limestones [12].

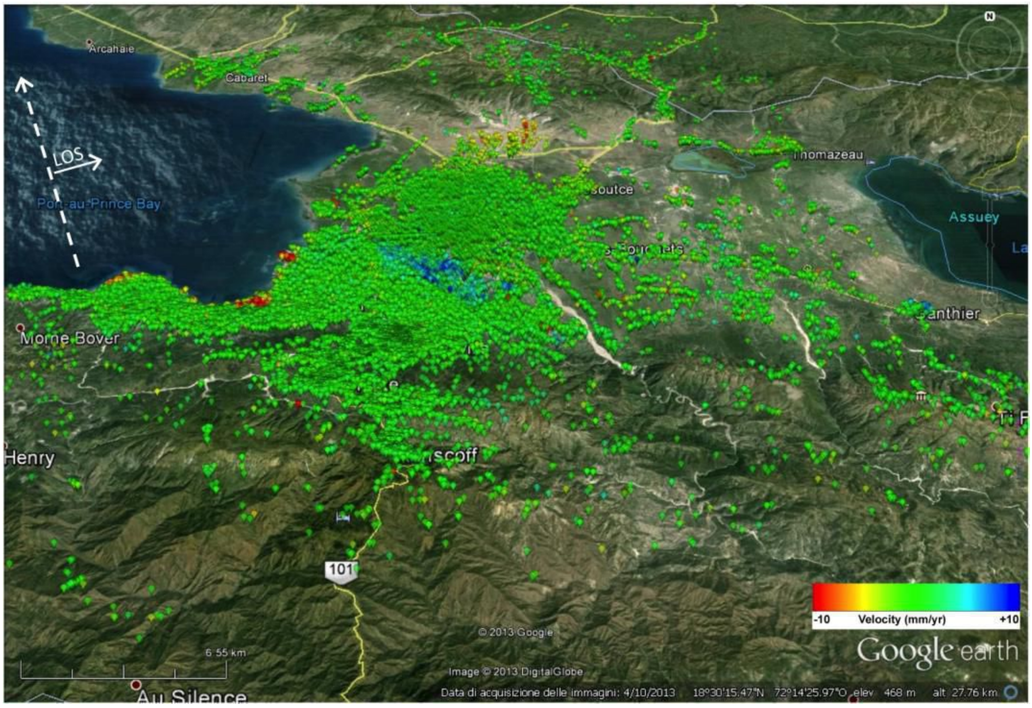


Figure 1. Distribution and average line of sight (LOS) velocity of radar targets (color dots) identified in the metropolitan area of Port-au-Prince, Haiti, and the surrounding regions; the targets are mainly human-made structures, rock outcrops, bare ground). Reddish to yellowish dots represent targets moving away from the satellite sensor and denote significant (up to few cm/year) subsidence affecting coastal areas. The background image is from Google Earth™.

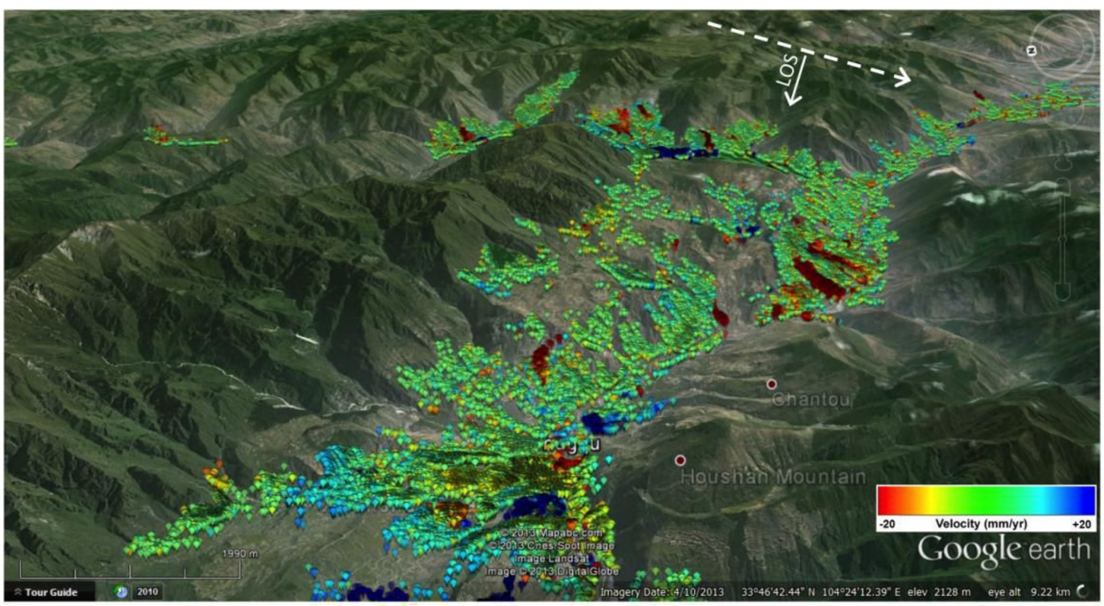


Figure 2. Distribution and average line of sight (LOS) velocity of radar targets in the Southern Gansu Mountains, China. Reddish and bluish dots represent targets moving, respectively, away from and toward the satellite sensor. The high density of targets, especially along the Bailong River valley, allowed the detection of numerous, large active landslides with average displacement rates exceeding 100 mm/year. The background image is from Google Earth™.

The initial MTI processing of 22 images (covering period January 2011-February 2012) focused on about 40 km$^2$ mountain terrain around the town of Zhouqu; this produced spatially dense information (more than 1000 radar targets/km$^2$) on ground surface displacements [7],[13]. A substantial portion of the radar targets showed significant displacements (from few to over 100 mm/yr), denoting widespread slope instability.

Here we present wide-area results from full CSK frame (~1700 km$^2$ coverage) processing, which lead to the identification of nearly 629,000 measurable radar targets. The average density of the targets (370/km$^2$) was suitable for the detection of numerous landslides (Fig. 2). In particular, the MTI results provided valuable information on the activity of several very large, very slow (<1.6 m/year) moving landslides that represent a persistent hazard to the local population and infrastructure, which are concentrated along the Bailong River valley. Indeed, in the past some of these landslides underwent periods of increased activity resulting in river damming and disastrous flooding [12].

## IV. CONCLUDING REMARKS

The case study examples presented in this work demonstrate that thanks to the wide-area coverage of satellite imagery (tens of thousands of square km), combined with a high spatial resolution (1-3 m) and improved re-visit frequency (days-weeks) of the new radar sensors, the millimeter precision MTI surveying can generate an unprecedented quantity (and quality) of information about ground surface displacements occurring in areas susceptible to slope or subsidence hazards. Furthermore, with regular globe-scale coverage and freely available imagery, new radar satellite background missions such as the European Space Agency's Sentinel-1 (https://earth.esa.int/web/guest/missions/esa-operational-eo-missions/sentinel-1) will guarantee ever increasing and more efficient use of MTI in ground hazard investigations. The widespread exploitation of high spatio-temporal resolution MTI data for both science and societal applications (including visualization and analysis) can be facilitated by Google Earth™ tools with free acess to high resolution optical imagery [10], or by new types of web-based participatory approaches including the so-called CrowdSourcing (e.g., Voluntered Geographic Information applications such as OpenStreetMap).

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