Dear Prof. Bruce Malamud,

Please find enclosed the revised version of our manuscript entitled “Brief Communication: Rapid Mapping Of Event Landslides: The 3 December 2013 Montescaglioso Landslide (Italy)”. Firstly, thanks for your time and effort spent in dealing with our manuscript. We have found the criticism, comments, and suggestions received from you and the referees very constructive, and we have considered all of them in the revised version of our work. As you suggested, and in order to comply with the referee’s requirements, we have slightly exceeded the number of references allocated for Brief Communications (24 instead of 20).

Please find here below for your reference the referee’s comments, and in **Bold** our replies. Changes in the manuscript text are highlighted in ***Bold Italic.***

Looking forward to receiving the final acceptance of our manuscript,

Sincerely yours.

Andrea Manconi
(Corresponding author)

Anonymous Referee #1
Received and published: 18 March 2014
Review of the manuscript “RAPID MAPPING OF EVENT LANDSLIDES: THE 3 DECEMBER 2013 MONTESCAGLIOSO LANDSLIDE (ITALY)” by A. Manconi et al. MS No.: nhess-2014-41

The manuscript by Manconi and coauthor describes a slope failure in Italy that occurred on 3 December 2013. The authors use a cross-correlation approach (if my guess is correct) applied to satellite radar data acquired by the Italian satellite CosmoSkymed. The Montescaglioso landslide was shown to move by as much as 30 m horizontally, with significant hazards associated. The authors discuss whether the landslide was associated with intense rainfall.
The data analysis done on the radar data is certainly excellent, showing a spectacular event that occurred few months ago. The figures are high quality and all necessary (in fact also the figures in appendix are relevant). The writing, however, is rather poor and to my opinion misleading. Given the sound scientific analysis of the data and relevance of this particular landslide event, I can recommend the publication of the manuscript. Major major major rewriting has to be done, however, as detailed below.

Our reply: We thank the referee for the detailed comments and constructive criticism, as well as for recognizing the importance and the scientific sound of the data and of the analysis presented in our manuscript. Here below we will provide our replies to all the major and minor points raised, as well as details on how we considered the referee suggestions in the revised version of

the manuscript.

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Major points

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1. Why the authors emphasize the "rapid" mapping and "rapid" analysis? This in fact was absolutely not clear. In the abstract alone, the word "rapid" can be found four times. Is a satellite imaging system that is acquiring every 16 days (the normal CosmosSkymed revisit period) so rapid? Other geophysical contributions dealing with rapid assessments after earthquakes and other hazards deal with timelines on the order of seconds or minutes. Here an analysis done weeks after a landslide hazard is not rapid. Please consider focusing on the geoscience contribution rather focusing on the "rapid" technique.

Our reply: We thank the Referee #1 for this comment. We have now modified the abstract in order to avoid repetitions of the word "rapid". The abstract now reads: "*We present a new approach to measure 3-D surface deformations caused by a large, rapid moving landslide, in an emergency scenario. The technique exploits the amplitude information of high spatial and temporal resolution SAR images captured by the COSMO-SkyMed satellites. Here we show the results obtained for the Montescaglioso landslide, southern Italy. Displacements have dominant planimetric SSW component, and exceed 10 meters among large part of the landslide deposit. Slope failure damaged a main road, private homes, and commercial buildings. Our results open to the possibility of preparing 3-D surface deformation maps shortly after the occurrence of large landslides.* "

We would like to remark that the main focus of our Brief Communication is indeed the assessment of 3-dimensional displacements shortly after an event landslide, and we intend to keep this focus. We think that mapping of 3-dimensional displacements shortly after an event by exploiting remote sensing techniques, and confirming the outcomes from such an analysis with those from field mapping, is a rather new concept in the context of landslide hazard, and to our knowledge this is the first example of successful application in an emergency scenario to support civil protection activities. We agree with the Referee #1 that in other contexts, such as earthquake hazard scenarios, the concept of "rapid" assessment is related to shorter timelines (minutes, or even seconds). But, in earthquake scenarios, these timelines are not referred to surface deformation mapping and/or assessment. To measure accurate 3-dimensional displacements relevant to earthquake scenarios in timelines of seconds or minutes, recent studies have shown that dense monitoring networks of continuous GPS stations might be a possibility in some areas, where location and extension of the potential seismogenic sources are known, and thus the GPS network might be installed in advance. This option is clearly unfeasible for event landslide scenarios, where location and extension of the phenomenon are usually unknown before the event occurrence.

2. The literature review in the introductions is flawed and needs to be rewritten. For instance, in line 20 and following: Obviously the authors are not aware of the current alternative methods applied to satellite and ground imaging data, such as image cross-correlation, DEM differencing, and others. Please also consult the numerous publications that have emerged following the earthquake induced landslides in Japan following the Tohoku disaster, many of the studies are published and referred to in a book (Earthquake-Induced Landslides: Proceedings of the International Symposium on ... by Keizo Ugai et al, Springer 2013). Also consider ground based InSAR systems (Corsini et al., 2006 and Jaboyedoff et al., 2010), determination of the average spatial shift by a cross-correlation function image pairs (White et al., 2003), Target Detection and Tracking (Veeraraghavan et al., 2006) and others. A recent paper published by Gance and coauthors (Engineering Geology Volume 172, 8 April 2014, Pages 26–40) will allow to get some overview on the current photogrammetric methods.

Our reply: We thank the Referee #1 for providing additional literature information, mainly on the analysis of optical images in landslide scenarios. As remarked by the Editor, the manuscript is intended for a Brief Communication, thus an in-depth literature review would be inappropriate. We would like to remark that we are well aware of the great advances performed in the last years on methods for the identification, measurement, and analysis of displacements based on image processing. However, most of the techniques mentioned by the Referee #1 are more relevant in a context where "monitoring" of surface displacements of an instable slope is necessary, and thus not completely relevant to our study. In our work, instead, we want to show how is possible to map and measure displacements of event landslides in areas that have not shown significant signs of instability before. High-resolution terrestrial photogrammetry methods (Gance et al., 2014) can be well applied only at locations where the instability has been already identified, and the monitoring network deployed. The same applies to other ground based monitoring systems, such as GB-InSAR or Terrestrial LiDAR.

Moreover, it is worth to remind that the quantitative exploitation of airborne and space-borne optical imagery with pixel-offset, target detection and tracking, etc., provide usually planimetric (2D) displacements, which in many cases are not sufficient for an accurate characterization of the landslide event, as well as to plan for monitoring and mitigation strategies in the event's aftermath. The same concept has been highlighted in a recent publication: (*Singleton et al., 2014, RSE, Volume 147, 5 May 2014, Pages 133–144)* "*However, optical images can only be used to assess purely horizontal movements (north–south and east–west directions) without consideration of the vertical component."* In addition, as mentioned in our Section 6, the use of optical imagery for rapid landslide mapping might be hindered by meteorological conditions: *"the availability of exploitable data strictly depends on the meteorological conditions at the acquisition time, as for example cloud coverage might compromise the visibility of the area of interest."*

Also, we are aware that DEM differencing based on the results of LiDAR surveys is an important tool to derive information on the topographic modifications due to landslides. However, in areas characterized by large planimetric motions (as the Montescaglioso landslide) the use of DEM differencing might result in misleading interpretations. Moreover, as we mentioned in Section 6: *"Airborne LiDAR associated with photogrammetric surveys represent also a powerful remote sensing methodology to map post-event landslide deformation, as well as to estimate the mobilized mass volume (e.g., Giordan et al., 2013). Further, the acquisition of LiDAR data might be in some cases hampered by the high costs and operational issues, as well as by unsuitable meteorological*

conditions in the event's aftermath."

3. Method is unclear. A section on methods is needed. Neither the PO method is detailed, nor the identification approach of fractures. How was the InSAR data processed. Detail the PO processing, which correlation term was used? Was it processed in the frequency domain? At which window and padding size? And so on.

Our reply: We have added now more specifications on the method used. However, we remind that the method applied to the Montescaglioso case-study has been already detailed in Casu et al., 2011. The PO technique used is based on the Normalized Cross Correlation approach implemented in the AMPCOR subroutine, which is part of the ROI_PAC code (Rosen et al., 2004). Specific details on the PO processing, such as the window size, were detailed in the caption of Figure 2: ***"In particular, we exploited the AMPCOR Fortran routine available in the ROI_PAC software (Rosen et al., 2004) using a matching window of 64×64 pixels. We calculated the PO considering a sparse grid with an under-sampling factor of four pixels. We applied a spatial smoothing filter to reduce high-frequency noise."*** **According also to the comments of the Referee #2, we have moved this section in the main text, in order to avoid misunderstandings. Since this paper is intended for a Brief Communication, we prefer to refer readers interested into more details on the processing approach to Casu et al, 2011, where the effect of different parameters relevant to the PO approach applied to SAR data are detailed and discussed extensively. The text now reads: "*Considering the poor quality of the DInSAR results, we applied the amplitude-based pixel-offset technique to the SAR data pairs across the event with the smallest spatial baselines, to reduce the impact of the spatial decorrelation. In particular, we considered the ascending 16 January 2013 - 18 December 2013, and the descending 10 January 2013 - 12 December 2013 data pairs, characterized by spatial baselines of 155 m and 40 m, respectively, and covering approximately the same time interval. In particular, for these data pairs we exploited AMPCOR, a Fortran routine based on the Normalized Cross Correlation approach, and available in the ROI_PAC software (Rosen et al., 2004). We considered a matching window of 64×64 pixels, and calculated the PO considering a sparse grid with an under-sampling factor of 4 pixels. We also applied a spatial smoothing filter to reduce high-frequency noise. Readers interested into more details of the PO processing used here are referred to (Casu et al., 2011).*"**

As concerns the identification of fractures (and, actually, of all the other surface features produced by the landslide), this was carried out following the approach in Parise (2003), in turn deriving from a number of studies therein cited. A sentence has been added in the text to clarify this point.

4. Please add a chapter on the geologic interpretation. How rainfall and the landslide are related (if any)? Common concepts have to be discussed, associated to shear stress and pore pressure increase.

Our reply: The geologic interpretation of the Montescaglioso landslide is beyond the scope of this paper. At the moment, several monitoring systems, as well as geological and geophysical investigations are ongoing. The results of these analyses are still preliminary, and will be the base of further research aimed at discussing the geological interpretation of this landslide event. The relationship between the event landslide and the rainfall, as well as the associated shear stress

and eventual pore pressure increase are under investigation and will be the subject of further research.

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Minor points

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1. Chapter 2, line 8: please add detail, how steep are the slopes. Facing which side? Is the configuration suited for your approach?

Our reply: Mean slope in the landslide area is around 10%, mainly facing South-South-East. We added now this information in the revised manuscript. The slope configuration is well suitable for the approaches used, as demonstrated by the PO results obtained, which are well in agreement with the field observations.

2. Chapter 2, line 10: please add a reference of the geological map authors/publisher

Our reply: The reference has been added.

3. Chapter 3, 1st paragraph: This is interesting but hard to read. Please restructure by first describing the earlier events. First discuss the October rain, second the December rain, third the landslide. Please also compare the rainfall to the seasonal rainfall, for instance: “in just 2 days a quarter of the annual rainfall was recorded”

Our reply: We thank the reviewer for this comment. We better describe now the temporal evolution of the events. Moreover we compare the October and December rainfall to the mean seasonal and annual values, as suggested. The text now reads: “*Between 5 and 8 October 2013, the general area between Apulia and Basilicata, including the town of Montescaglioso, was struck by a heavy rainfall event with a cumulated rainfall E = 246 mm, and a mean rainfall intensity I = 3.6 mm·h-1. The event caused widespread flooding, numerous shallow landslides, severe economic losses, and four fatalities. Moreover, from 30 November (14:00 CET) to 2 December (22:00 CET), with a cumulated rainfall measured at the Ginosa rain gauge, located 8 km from Montescaglioso, of E = 151.6 mm, and mean rainfall intensity I = 2.7 mm·h-1. The two events totalized about 70% of the mean annual rainfall concentrated in few days.* ”

4. Chapter 4, 1st paragraph. The analysis of the historical imagery would be worth to show in the paper or in the appendix. Figure S1 is only an interpretation of a data set that is not shown in the manuscript, analysed with a method that is not explained in the manuscript. At least the authors could create a composite map, using different images in different channels, to show the changes in a figure.

Our reply: We thank the reviewer for this comment. In the revised version, we have better detailed the approach followed for the multitemporal inventory based on the interpretation of stereoscopic aerial photographs. In the Supplementary material, we added a table (S5) related to the aerial photographs used to produce the multitemporal inventory map.

5. Figure S1 and S2 could go into the main text, including descriptions. The figure S2 shows the structural summary, that would be important to be compared to the displacement maps of figs 2 and 3.

Are any of the structures mapped active? Are any structures active, or does the PO method not have the resolution and sensitivity to localize such?

Our reply: Figures in for the main text in NHESS Brief Communications are limited to 3. For this reason, also in the revised version of the manuscript we have kept Figure S1 and S2 in the supplementary information.

6. Chapter 4, 2nd paragraph: photographs taken during helicopter flights: these are not provided, neither in the manuscript nor in the appendix. Figure S2 is not the one referred to in the text.

Our reply: We thank the referee to point out the inconsistency. In the revised version, we have now included the Figure S6, relevant to a photograph taken form helicopter in the event's aftermath.

7. Chapter 4, 2nd paragraph: How are the "geomorphological features" identified?

Our reply: The geomorphological features were identified directly in the field, carrying out detailed surveys in the days immediately following the event. Many features were in fact canceled after 5 days, due to the need to create temporary roads for civil protection issues. The text has been slightly changed by adding a sentence to better explain the approach followed.

8. Chapter 5, 2nd paragraph: How was the dinsar data processed?

Our reply: We have now added more details on the DInSAR processing. The text now reads "*A first conventional DInSAR analysis was performed on the acquisitions across the investigated event, by following the approach detailed in Massonet et al., 1993. Moreover, spectral shift compensation and interferometric fringes filtering were carried out (Burgmann et al., 2000).*"

9. Chapter 5, 3rd paragraph: How was the PO processing set up? FFT? Window size? Oversampling? Masking? Correlation function? Multi pass? No words about these!

Our reply: Please see also our reply to Major point 3

10. Chapter 6, 1st paragraph: Completely change the scope. Omit the "rapid" discussion and focus more on the geoscientific results provided.

Our reply: Please see our reply to Major point 1 and Major point 4.

11. Chapter 6, 2nd paragraph: the sentence that "optical data can usually provide qualitative information only" is simply wrong, outdated and shows that the existing literature was not considered.

Our reply: Please see our reply to Major point 2.

Summary. I am aware that my comments are very critical. But the manuscript has many very valuable contents that are worth publishing. I hope my criticism help to reflect and improve this early stage manuscript.

Anonymous Referee #2
Received and published: 26 March 2014

Dear editor,
Thank you for the opportunity to revise the paper titled "Brief communication: Rapid mapping of event landslides: the 3 December 2013 Montescaglioso landslide (Italy)". The main contribution of this work is the application of the pixel offset technique (PO) to measure 3D surface deformation of a large rapid moving landslide in an emergency situation (Montescaglioso, 3rd December 2013). The PO technique was used to exploit ascending and descending SAR image datasets captured by the COSMO-SkyMed. The 3-D ground deformation measurements confirmed the deformation mechanisms recognized and mapped through geomorphological and field mapping.
This reviewer recognises the scientific value provided by this work and recommends its publication. Below you will find some minor comments aiming to improve the quality of the manuscript.

Our reply: We thank the Referee #2 for recognizing the scientific value provided by this work. Please find below our detailed answer to the minor comments provided.

Minor comments:
Abstract: please consider to include retrieved results in terms of magnitude and direction of displacement measured with the proposed techniques/ approach. Note that measured displacements, up to 20 m, clearly overpass the detection thresholds of DInSAR techniques.

Our reply: We thank the Referee #2 for this comment. We have now included information on the results in the abstract, which now reads: "*We present a new approach to measure 3-D surface deformations caused by a large, rapid moving landslide, in an emergency scenario. The technique exploits the amplitude information of high spatial and temporal resolution SAR images captured by the COSMO-SkyMed satellites. Here we show the results obtained for the Montescaglioso landslide, southern Italy. Displacements have dominant planimetric SSW component, and exceed 10 meters among large part of the landslide deposit. Slope failure damaged a main road, private homes, and commercial buildings. Our results open to the possibility of preparing 3-D surface deformation maps shortly after the occurrence of large landslides.* "

Lines 10-12 page 1457: the authors comment about DInSAR limitations to measure rapid deformations but no references nor values are provided. I suggest quantifying DInSAR detection thresholds, which could be useful to compare them with the detection capacity of the PO technique. One way of doing this is to include some literature examples illustrating DInSAR detection limits for landslides (Wasowski et al.2014. Investigating landslides and unstable slopes with satellite Multi Temporal Interferometry: current issues and future perspectives. Engineering Geology; Strozzi et al.2013. Interpretation of aerial photographs and satellite SAR interferometry for the inventory of landslides." Remote Sensing). Note that standard DInSAR processing of ALOS PALSAR image has permited to detect over to 1 m/yr in certain case studies (see García et al. 2013. DInSAR analysis of ALOS PALSAR images for the assessment of very slow landslides: the Tena Valley case study.Landslides.)

Our reply: We thank the referee for pointing out this issue. In the revised version of the

manuscript, we have now included some of the references suggested, in order to highlight the limitations and the detection thresholds of DInSAR. The text now reads:

Section 1: "*The main advantage of DInSAR is the possibility to measure sub-centimetric surface displacements over large areas (10^2-10^5 km^2). However, in landslide scenarios DInSAR can be limited by the unsuitable exposure of the instable slope area with respect to the acquisition geometry, as well as by large and/or rapid displacements, which may overcome the maximum detectable surface velocities between consecutive SAR acquisitions (Wasowski and Bovenga, 2014). In the latter case, interferometric phase information may be affected by high fringe rates leading to processing difficulties in the phase unwrapping step, and/or to coherence loss due to misregistration errors (Casu et al., 2011).*"

Section 6: "*When the slope exposure is suitable with the satellite acquisition geometry (Colesanti and Wasowski, 2006), space-borne SAR can be considered as a valid alternative to map and measure surface deformation relevant to landslide phenomena. This technique has the main advantage to acquire data day and night, as well as in any weather condition. In some particular case studies DInSAR processing of L-Band SAR imagery permitted to detect and measure landslide surface velocities up to 1 meter/year (Garcia et al., 2013). Though, as mentioned in the introduction, the exploitation of conventional DInSAR technique in large and catastrophic landslide scenarios is hindered by the very large and/or rapid deformation usually associated with this kind of events.*"

Lines 21-24 page 1471: overall a larger explanation on how the PO and the 3D methods were applied would be useful. Information relevant to the PO technique and generation of the 3D surface deformation map is included in the captions of Figures 2 and 3 and not in the text. Please consider to extend the explanation on the manuscript of both the PO technique and the 3D approach.

Our reply: We thank the Referee #2 for this comment. As highlighted also by the Editor, the manuscript is intended for a Brief Communication, thus a detailed description of the herein used methodology is unsuitable. We refer the readers interested into more details on the PO technique to Casu et al., 2011, where the technique is extensively explained. Moreover, the approach used here to obtain the 3D displacements is straightforward, and well explained in Racoules et al., 2013 and Hu et al., 2014"

Line 25 page 1470: being a technique claimed to improve landslide event emergency management, I suggest to include the duration (days or hours) of the 3-D surface deformation technique from image acquisition to "real" or "potential" delivery to civil protection.

**Our reply: We thank the Referee #2 for highlighting this point, which is the main focus of our contribution. We have now included this information in the revised version of the manuscript. The text now reads: "*The application of the PO technique to get rapid assessment of surface displacements after an event depends on two main factors: (i) the availability of SAR imagery, which is constrained by the satellite configuration and predefined acquisition plan; (ii) the PO processing time to get 3-D deformation maps. Considering our case study, CSK imagery was available after 8 and 15 days, for descending and ascending orbits, respectively. This was possible also because the CSK acquisition plan was modified specifically for the Montescaglioso emergency scenario. The 3-D deformation maps computed via the PO technique were ready to be delivered to the civil protection*" **

***authorities in less than 24 hours after receiving the SAR imagery. Depending on the area of interest and on the acquisition plan, CSK configuration may provide SAR images also with shorter revisit times. Thus, PO results can be potentially produced and delivered in timelines of few days after the event landslide.*”**

Figure 1. Explain what D and E represent

Our reply: Done, thanks for pointing out this inconsistency.

Brief Communication

RAPID MAPPING OF EVENT LANDSLIDES: THE 3 DECEMBER 2013 MONTESCAGLIOSO LANDSLIDE, ITALY

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Abstract

We present an approach to measure 3D surface deformations caused by large, rapid moving landslides using the amplitude information of high resolution, X-band SAR images. We exploit SAR data captured by the COSMO-SkyMed satellites to measure the deformation produced by the 3 December 2013 Montescaglioso landslide, southern Italy. The deformation produced by the deep-seated landslide exceeded 10 meters, and caused the disruption of a main road, a few homes and commercial buildings. The results open to the possibility of obtaining 3D surface deformation maps shortly after the occurrence of large, rapid moving landslides using high resolution SAR data.

Key words: Landslide mapping, emergency scenario, SAR, pixel-offset, surface deformation monitoring, Montescaglioso, southern Italy.

1. Introduction

Large landslides occur in several regions of the Earth, causing damage and casualties (Petley, 2012). In places, these phenomena affect urban areas, buildings, roads and rails, threatening the population and causing emergency situations. In such scenarios, rapid mapping of the location and extent of the surface deformation caused by large landslides can provide important hints for the rapid response of civil protection authorities, for rescue and recovery operations, and to design and deploy effective monitoring systems (Giordan et al., 2013). Most commonly, post-event landslide maps are compiled through field mapping, and/or the visual analysis of aerial photographs taken shortly after a landslide event (Guzzetti et al., 2012). Where the ground displacements are in the order of several meters, and the velocity of the failure is rapid to very rapid (Cruden and Varnes, 1996), access to the landslide area may be difficult or impossible, or too dangerous to perform field mapping. In these circumstances, remote sensing techniques provide an effective alternative to perform semi-quantitative or quantitative assessments of the extent and the amount of the ground deformations (Singleton et al., 2014, and references therein).

Among several remote sensing techniques, space-borne Synthetic Aperture Radar (SAR) has demonstrated its efficiency to monitor changes on the Earth's surface produced by natural and human induced processes (Rott, 2009). In particular, Differential SAR Interferometry (DInSAR) allows measuring ground deformation by analysing the phase difference between two SAR images (Massonnet et al., 1993) acquired over the same area at different times and from different orbital positions (hereafter referred to as temporal and spatial baselines, respectively). The main advantage of DInSAR is the possibility to measure sub-centimetre surface displacements over large areas (10^2-10^5 km^2). For studying landslides, the application of DInSAR techniques can be limited locally by the unsuitable exposure of the unstable slopes with respect to the acquisition geometry, and by large and/or rapid displacements, which may overcome the maximum detectable surface velocities between consecutive SAR acquisitions (Wasowski and Bovenga, 2014). In the latter case, interferometric phase information may be affected by high fringe rates leading to processing difficulties in the phase unwrapping step, and/or to coherence loss due to misregistration errors (Casu et al., 2011). If the deformation introduces geometric distortions without significantly affecting the SAR image reflectivity, displacements can be observed in the amplitudes of the SAR image pairs acquired before and after the event, with a method hereinafter referred to as "pixel-offset" (PO).

Compared with standard DInSAR, the PO approach applied to SAR imagery provides 2-D displacement information i.e., the displacement components across and along the satellite's track (range and azimuth direction, respectively). Ground displacements that can be detected using the PO approach are around 1/10 to 1/20 of the pixel size, which for modern SAR sensors is in general in the order of a few meters. The PO approach provide an additional and complementary tool to analyse and interpret surface deformations in areas where standard DInSAR techniques are hindered by geometrical or morphological constrains (e.g., Manconi and Casu, 2012). Although the PO approach is becoming popular to monitor ground displacements in unstable slopes (Gance et al., 2014), the approach has been so far rarely applied to event landslide scenarios, and in general the majority of the studies have considered optical imagery (Singleton et al., 2014 and references therein).

In this work, we present the first results of a rapid mapping effort conducted during a recent landslide emergency occurred in 3 December 2013 in the Montescaglioso municipality, Basilicata, southern Italy (**Fig. 1**). In the following, we first describe the main features of the event landslide. We then present qualitative and semi-quantitative information obtained immediately after the event using consolidated mapping approaches (Guzzetti et al., 2012). Next, we show the surface deformation map obtained using the PO technique applied to high-resolution SAR images acquired by the COSMO-SkyMed (CSK) satellites before and after the landslide event. PO analyses of SAR images captured along ascending and descending orbits allowed to retrieved the full three-dimensional deformation field caused by the landslide (Raucoules et al., 2013; Hu et al., 2014).

2. Local setting

A large landslide struck the SW slope of Montescaglioso, a town located in the Matera Province, southern Italy, on 3 December 2013, after 56 hours of continuous rainfall (**Fig. 1**). As many other towns in southern Italy, Montescaglioso was built at the top of a hill bounded by steep slopes affected by multiple landslides of different types (Cruden and Varnes, 1996). In particular, the slope affected by the new landslide is characterized by large, deep-seated, ancient slope failures (Boenzi et al., 1971). Annual rainfall in the area averages 570 mm, with most of the rainfall falling in November (187 mm). In the general area crop out sediments of the "Bradanic trough", Pleistocene in age (Tropeano et al., 2002), including a regression (coarsening upward) sequence made up of clay (at the bottom), sand and gravel (at the top). In the slope affected by the new Montescaglioso landslide, sediments are heterogeneous, as demonstrated by the presence of large blocks of conglomerates (with a maximum size of about 5 m × 3 m) found at different elevations in the slope. We attribute the chaotic distribution of the materials to repeated, old and very old landslides; the result of a complex morphological evolution of the area.

3. The new Montescaglioso landslide

Between 5 and 8 October 2013, the general area between Apulia and Basilicata, including the town of Montescaglioso, was struck by a severe rainfall event with cumulated rainfall E = 246 mm, and mean rainfall intensity I = 3.6 mm·h^{-1}. The regional rainfall event caused widespread flooding, numerous shallow landslides, severe economic losses, and four fatalities. A second rainfall event hit the Montescaglioso area in the period from 30 November, 14:00 CET, to 2 December, 22:00 CET, with a cumulated rainfall measured at the Ginosa rain gauge, eight kilometers from Montescaglioso, of E = 151.6 mm, and mean rainfall intensity I = 2.7 mm·h^{-1}. The two events exceeded 70% of the mean annual precipitation.

The length of the landslide measured along the main displacement axis is $L_L \sim 1.2\times10^3$ m, and the width measured perpendicularly to the main axis is $W_L \sim 8.0\times10^2$ m, for a total landslide area $A_L \sim 3.0\times10^5$ m^2. The deep-seated slope failure occurred along a SSW facing slope, and extended from ~200 m of elevation in the source area to ~110 m of elevation at the toe, with an average terrain gradient of ~10%. Movement of the landslide damaged or destructed more than 500 m of the main road connecting the town of Montescaglioso to the Province Road SP175. The large failure involved a few warehouses, a supermarket, and private homes located on the right bank of a channel in the area known as "Cinque Bocche" (**Fig. 1**). Anecdotal information collected immediately after the event reveals that the landslide was rapid (Cruden and Varnes, 1996), with the main movement occurring in a short period of 15-20 minutes, corresponding to an estimated average velocity of about 0.5-1 meters/minute. The movement started at 13:05 CET, and affected the road shortly afterward. Next, the movement involved the lower-left flank of the landslide, resulting in the formation of a swarm of scarps and counter-scarps, several tens of meters in length and with a maximum height of seven to eight meters. A house (shown by "C" in **Fig. 1**) was moved a few meters downslope and tilted. Fortunately, the building did not collapse, and allowed the inhabitants to escape avoiding direct consequences.

4. Geomorphological mapping of the new Montescaglioso landslide

To respond to a request of the Italian National Department for Civil Protection (DPC), in the period from 9 to 24 December 2013, immediately after the landslide, we conducted an initial geomorphological analysis to prepare a preliminary landslide inventory map, and to characterize the new Montescaglioso landslide in the context of the pre-existing landslides in the study area. This was done through the visual interpretation of seven sets of 30 black-and-white stereoscopic aerial photographs taken from 1947 to 2003, at scales ranging from 1:24,000 to 1:36,000 (**Table S5** in Supplementary Material). The aerial photographs were obtained as images in JPG format at low resolution (88 dpi of the negative) from the online catalogue of aerial photographs of the Istituto Geografico Militare Italiano (IGMI, http://www.igmi.org/voli/). The images were printed, and visually analysed using a mirror "double vision" stereoscope with image magnifications ranging from 1.5× to 15×. Despite the low resolution of the aerial photographs, visual inspection allowed to identify and map a large number of geomorphological features related to the presence of pre-existing mass movements in the area. A set of photographical characteristics and morphological features were examined on the stereoscopic aerial photographs, including shape, size, photographic colour, tone, mottling, texture, pattern of objects, site topography, and setting (Guzzetti et al., 2012). The geomorphological features were drawn on transparent plastic sheets placed over the aerial photographs, and then digitized exploiting GIS software and a 2006 digital ortho-photomap available through a WMS service provided by the Italian Environmental Ministry (http://www.pcn.minambiente.it).

The geomorphological landslide map shows (**Fig. S1** in Supplementary Material): (i) a large, very old landslide, largely dismantled by erosion processes, including other landslides, that affected the entire slope, (ii) a number of smaller and more recent landslides, mainly translational slides and flows, which are distributed within and at the edges of the pre-existing, very old landslide, and (iii) numerous, mostly minor, landslide escarpments. Inside the pre-existing, very old landslide we recognized different generations of landslides. Some of these landslides affect the town of Montescaglioso (**Fig. S1** in Supplementary Material).

In addition to the interpretation of the stereoscopic aerial photographs, we performed field surveys to evaluate the main consequences of the landslide, and to compile a map of the surface deformations in the landslide area, aimed at identifying zones within the landslide mass that showed different kinematics (Parise, 2003, and references therein). The field surveys were aided by the visual analysis of post-event terrestrial photographs, and photographs taken during helicopter flights (see **Fig. S2** and **Fig. S6** in Supplementary Material). The geomorphological features mapped in the field and through the inspection of the terrestrial and the helicopter photographs included single fractures, sets of fractures, tension cracks, trenches up to six meters in depth or width, and pressure ridges. Many of the geomorphological features mapped immediately after the landslide event were later destroyed by the construction of temporary roads.

5. Three-dimensional surface deformation from space-borne SAR

The Italian Space Agency (ASI) made available a set of X-band CSK images for the study area. The dataset consists of 31 images taken along ascending orbits in the period from 30 January 2012 to 18 December 2013, and 12 images taken along descending orbits in the period from 21 March 2012 to 12 December 2013. Both sub-sets included a post-event image.

First, we performed a conventional DInSAR analysis exploiting acquisitions taken across the investigated event, suing the approach proposed by Massonet et al. (1993). In addition, we carried out spectral shift compensation and interferometric fringes filtering (Burgmann et al., 2000). However, in the area affected by the new Montescaglioso landslide the conventional DInSAR processing produced unsatisfactory results, which were primarily attributed to the excessive fringe noise related to the fast-moving deformation pattern of the landslide (**Fig. S3** in Supplementary Material). We note that the retrieved DInSAR signal is generally very noisy also in areas located near (but outside of) the new Montescaglioso landslide. We consider this a consequence of the large temporal and/or spatial baselines that characterize the available CSK image pairs across the landslide event and, in general, the entire data distribution (**Fig. S4** in Supplementary Material).

Considering the poor quality of the DInSAR results, we applied the amplitude-based, pixel-offset technique to the SAR data pairs across the event with the smallest spatial baselines, to reduce the impact of the spatial decorrelation. In particular, we considered the ascending 16 January 2013 - 18 December 2013, and the descending 10 January 2013 - 12 December 2013 data pairs, characterized by spatial baselines of 155 m and 40 m, respectively, and covering approximately the same time interval (336 days and 332 days, respectively). For these data pairs, we exploited AMPCOR, a Fortran routine based on the Normalized Cross Correlation approach, available in the ROI_PAC software (Rosen et al., 2004). We considered a matching window of 64×64 pixels, and calculated the PO considering a sparse grid with an under-sampling factor of 4 pixels. We applied a spatial smoothing filter to reduce high-frequency noise. Readers interested in the details of the PO processing used here are referred to Casu et al. (2011).

As mentioned already, the PO technique allows identifying with a good spatial resolution areas affected by large displacements, which are on the order of, or exceed the pixel size e.g., three meters for the available CSK data. Combining the PO measurements obtained exploiting the CSK ascending and descending orbits, we determined the three-dimensional deformation pattern caused by the new Montescaglioso landslide (**Fig. 2**). Visual inspection of **Fig. 2** reveals that the ground displacements have a dominant SSW component, with values exceeding 10 meters for large parts of the landslide deposit, and exceeding locally 20 meters. Significant subsidence values were identified in the areas experiencing the largest damages, whereas a distinct uplift of up to five meters was detected close to the accumulation area.

6. Discussion and Conclusions

The exploitation of remote sensing data and technologies for the rapid mapping of natural and/or human induced disasters is becoming a standard practice to support civil protection emergency and recovery operations (Boccardo, 2013). This includes analyses of data acquired from different remote platforms (e.g., ground based systems, manned and unmanned aerial systems, space-borne systems), and exploiting different types of sensors (e.g., panchromatic, multispectral, hyperspectral, thermal, LiDAR, radar). For large landslides, selection of the most appropriate mapping and monitoring technique depends on multiple factors (Wieczorek and Snyder, 2009; Giordan et al., 2013). After a new landslide event, rapid evaluation of the area affected by the mass wasting, and measurements of the associated surface deformations, are of primary interest to design and deploy effective monitoring networks, and to support early warning systems ~~aimed at ensuring the safety of people, structure and infrastructures~~. Post-event deformation maps can also contribute to improved geomorphological analyses and geophysical investigations, and prove useful for the evaluation of the residual risk, and for the selection, the design, and the implementation of mitigation and stabilization measures (Revellino et al., 2010).

Most commonly, optical images captured by aerial and satellite sensors before and after a landslide event are used for first order evaluations of ground displacements in emergency scenarios. However, optical data can only provide qualitative and/or semi quantitative bi-dimensional information, and the possibility of obtaining optical data of sufficient quality depend on local meteorological conditions. Frequently, during and immediately following the occurrence of rainfall-induced landslides, cloud coverage limits the visibility of a landslide area. Airborne LiDAR represents an additional remote sensing tool to detect and map post-event landslide deformation, and to estimate the volume of the displaced mass (e.g., Giordan et al., 2013). However, the acquisition of LiDAR data can be limited by multiple operational constrains, including the local meteorological conditions, and the costs of the surveys.

Where the setting of the local terrain is suitable for the satellite acquisition geometry (Colesanti and Wasowski, 2006), space-borne SAR is a valid alternative to detect, map and measure surface deformations caused by active landslides. SAR data can be captured in all weather conditions, during the day and the night, with a significant advantage over other remote sensing techniques, and chiefly the techniques based on optical (multispectral) data. Although, conventional DInSAR techniques have known limitations for detecting and measuring the deformation of rapid moving landslides, Garcia et al. (2013) have shown recently that processing of L-Band SAR imagery was capable of detecting and measuring landslide surface velocities up to one meter per year.

We have shown that the amplitude information captured by space-borne SAR images can be exploited to detect, map, and measure deformations caused by large, rapid-moving landslides. For the purpose, we exploited the “pixel offset” (PO) technique (Rosen et al., 2004).) using pairs of SAR image acquired before and after the new Montescaglioso landslide by the CSK satellites, which ensures high spatial resolution (3 m × 3 m) and short revisit times (16 days on average for the available datasets). We combined the PO results obtained from ascending and descending orbits to retrieve the three-dimensional geometry of the ground displacements. To our knowledge, this is the first time that this approach was applied to the rapid mapping of the 3D surface displacement of rapid-moving landslides. The application of the PO technique to obtain a rapid assessment of the surface displacements after an event depends on two main factors: (i) the availability of SAR imagery, which is constrained by the satellite configuration and predefined acquisition plan, and (ii) the PO processing time. For the Montescaglioso landslide case study, the CSK imagery was made available to us 8 and 15 days after the landslide event, for the descending and the ascending orbits, respectively. To obtain this result, the CSK acquisition plan was modified specifically to contribute to the Montescaglioso civil protection emergency scenario. The 3D deformation maps computed exploiting the PO technique were delivered to the civil protection authorities less than 24 hours after receiving the SAR imagery. Depending on the area of interest and the acquisition plan, the CSK configuration may provide SAR images with shorter revisit times. In principle, PO results can be produced and delivered just a few days after an event landslide.

The combination of rapid geomorphological mapping, rapid field mapping, and rapid measurements of 3D deformation proved crucial to support civil protection authorities during the emergency following the new Montescaglioso landslide. The results of the geomorphological multi-temporal analysis allowed recognizing the presence of pre-exiting landslides of different size, shape, and relative age, and that affect larger areas than those identified in existing official maps and reports. The field mapping performed shortly after the event allowed to obtain useful information to better understand the kinematics of the new landslide, and for the reconstruction of the geometry of the slip surface (Parise, 2003). Two major landslide scarps were identified in the area. A first scarp, located in the middle of slope in the area where the supermarket was located, formed during the initial phase of movement. A second scarp, located closer to the divide, generated presumably during a second phase of movement, as a result of the retrogressive evolution of the landslide. The 3D ground deformation measurements obtained through the PO analysis detected two main directions of movement associated with (**Fig. 3**) (i) the main landslide event (SSW), and (ii) a secondary and smaller event (SSE). Thus, the PO results are in agreement with the magnitude and the deformation mechanisms recognized and mapped in the field. The combined interpretation of the results obtained with classical and new methods presented in this work was essential for the design of the topographic monitoring network installed in the Montescaglioso area. We expect the results obtained to be useful for the selection and the design of the mitigation strategies that will be implemented in the landslide area, and in the neighbouring regions.

Finally, we note that future integrations of information obtained exploiting classical geomorphological analyses and SAR images, through DInSAR and/or PO techniques, might open new scenarios for the analysis of rapid-moving landslides characterized by complex spatial and/or temporal heterogeneities of the deformation field. We expect that the increasing availability of space-borne, high spatial and/or temporal resolution SAR images, such as COSMO-SkyMed and TerraSAR-X, and the forthcoming ALOS PALSAR-2 and Sentinel missions, will enhance the possibility to perform the rapid mapping of large landslides in complex emergency scenarios, and to support civil protection authorities in the aftermath of catastrophic landslide events.

7. Acknowledgements

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Figures

Figure 1. Montescaglioso, southern Italy. The red area shows the ~~approximate~~ area affected by the 3 December 2013 Montescaglioso landslide. Location of a supermarket (A), and of most damaged buildings (B and C) is shown. (D) and (E) show locations of the Cinque Bocche and Capoiazzo channels. Source of terrain map: Google Earth™.

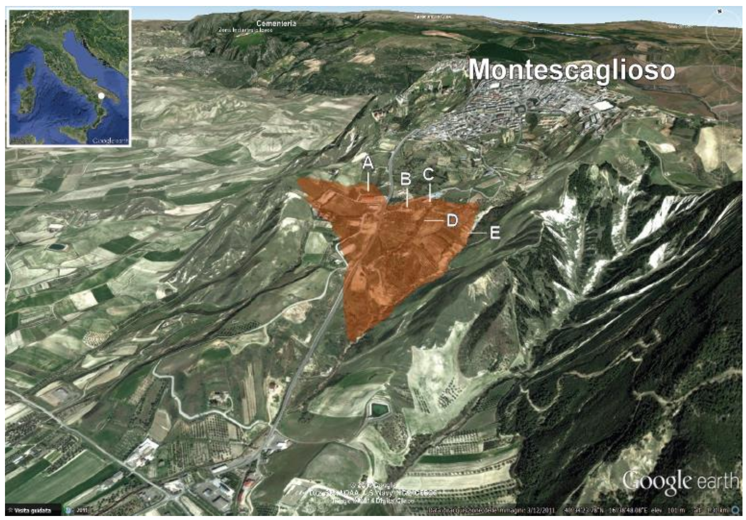


Figure 2. The new Montescaglioso landslide of 3 December 2013. Pixel-offset results for the (a) East-West, (b) North-South, and (c) Up-Down components of the surface deformation. Measurements are the results of the combination of pixel-offset results obtained processing COSMO-SkyMed images acquired along ascending and descending orbits.

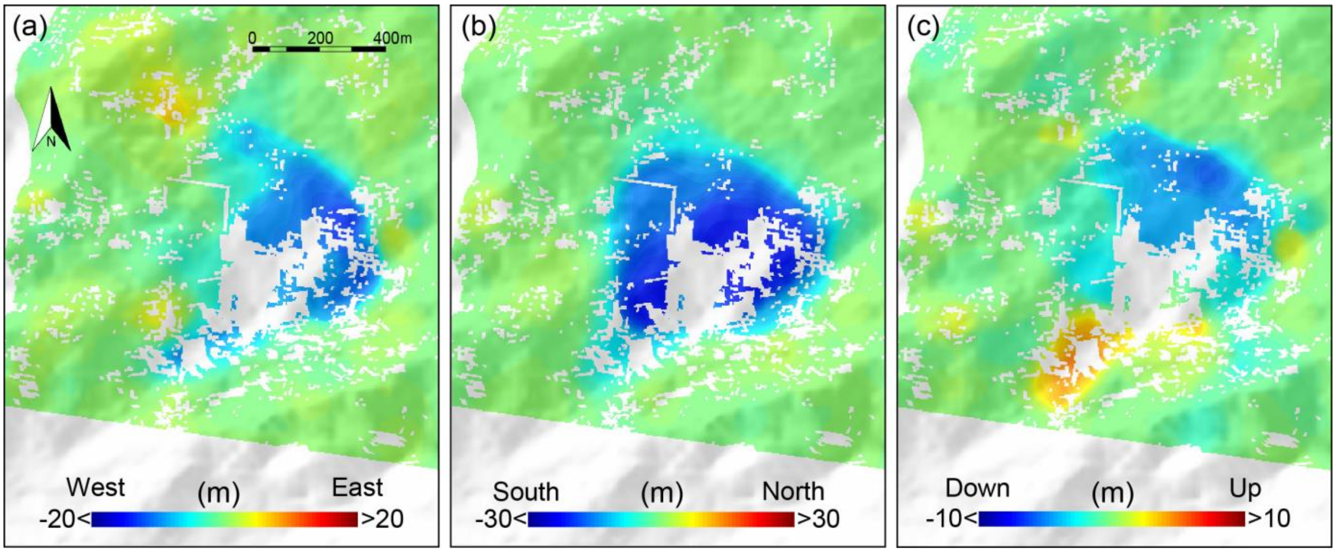
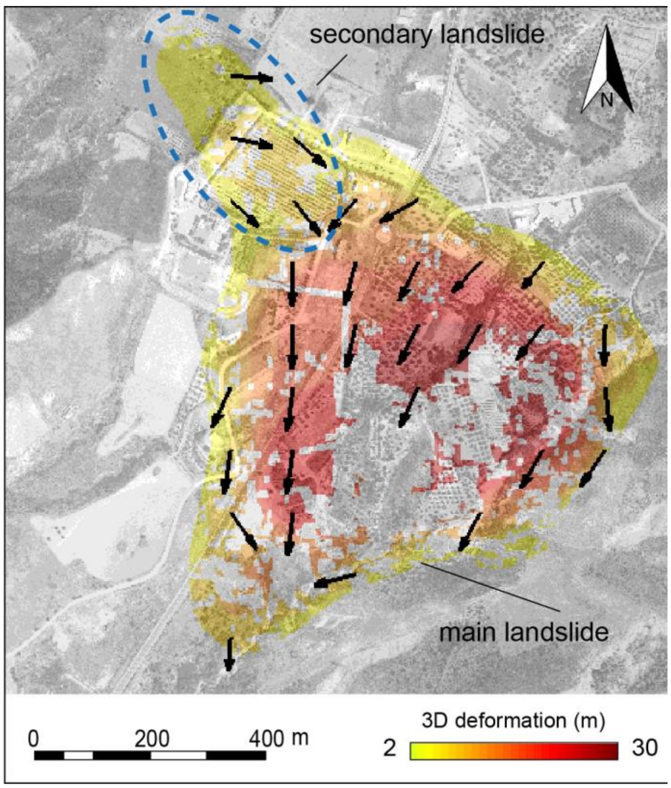
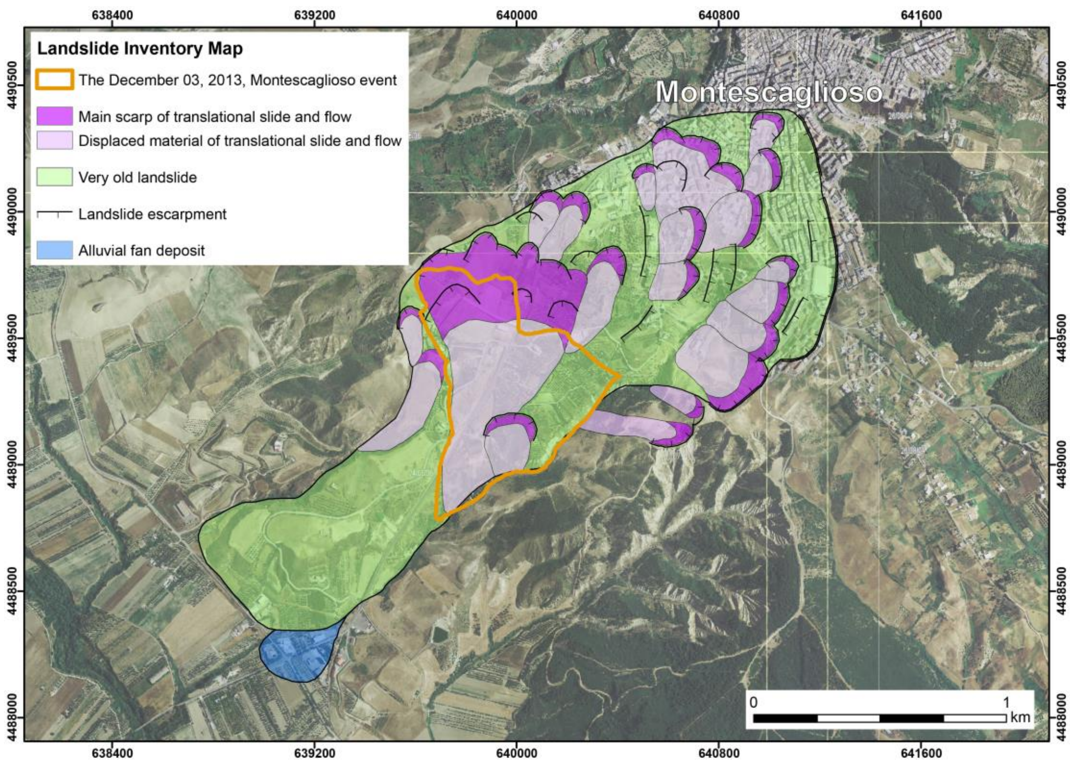


Figure 3. The new Montescaglioso landslide of 3 December 2013. Map of the surface deformation obtained through the Pixel-Offset (PO) analysis prepared using the ©3DA approach (Allasia et al., 2013). Colours show magnitude of the 3D deformation field. Arrows show direction of movement (unit vectors) derived from the PO analysis in the EW-NS plane. Deformations smaller than two meters are not shown. The deformation field shows two main directions of motion: (i) a dominant SSW direction caused by the main landslide, and (ii) a secondary SSE direction caused by a parasitic landslide, encompassed by the dashed blue ellipse.

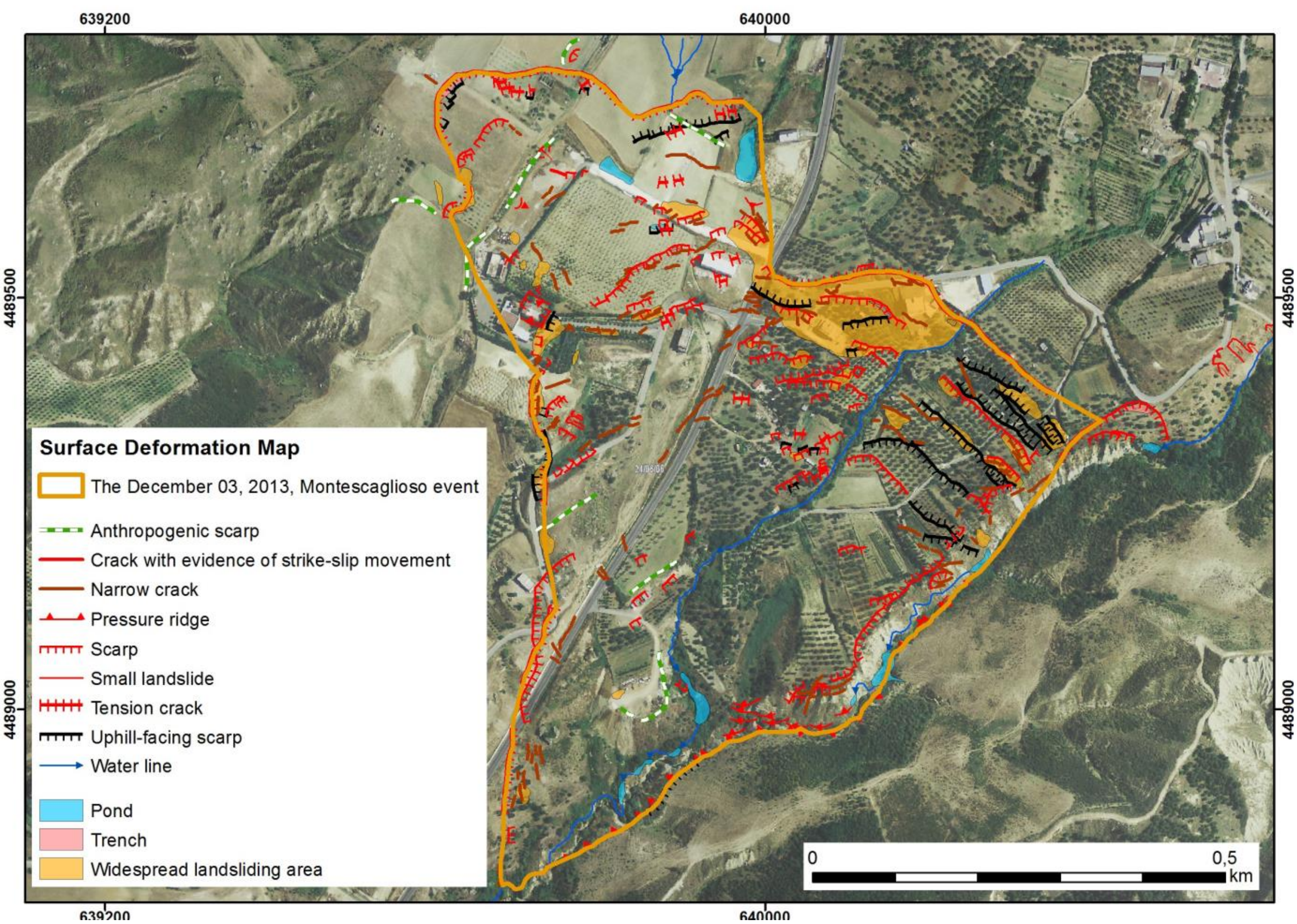


Supplementary Material of the Manuscript

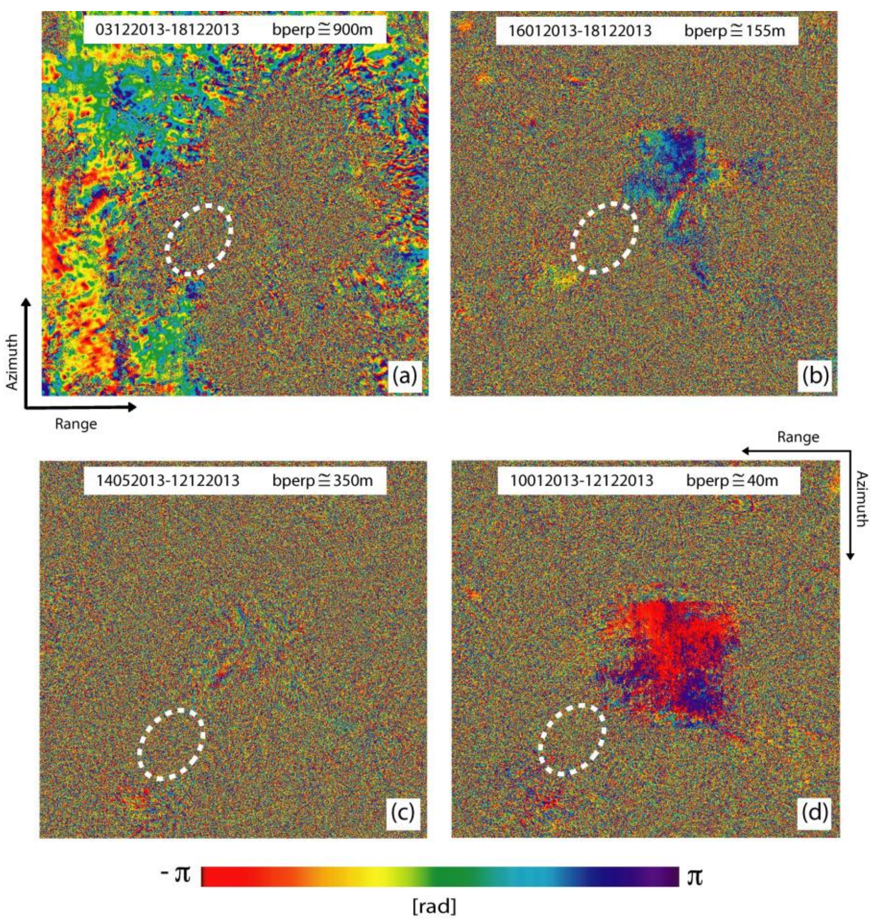
S1. Landslide inventory map realized along the SW slope of the hill where is located the Montescaglioso village. The map is carried out by the photointerpretation of different sets of stereoscopic aerial photographs taken in the period 1947-2003. The map shows: (i) a very old landslide (light green in the map); (ii) slide, slide flows and flows (violet in the map) distributed inside and at the boundary of the very old landslide; (iii) main landslide escarpments and (iv) alluvial fan deposit (light blue in the map). Superimposed to the pre-existing landslides, in orange is represented the 3 December 2013, Montescaglioso landslide. The base map is the WMS 2006 color orto-photomap, downloaded from http://www.pcn.minambiente.it.



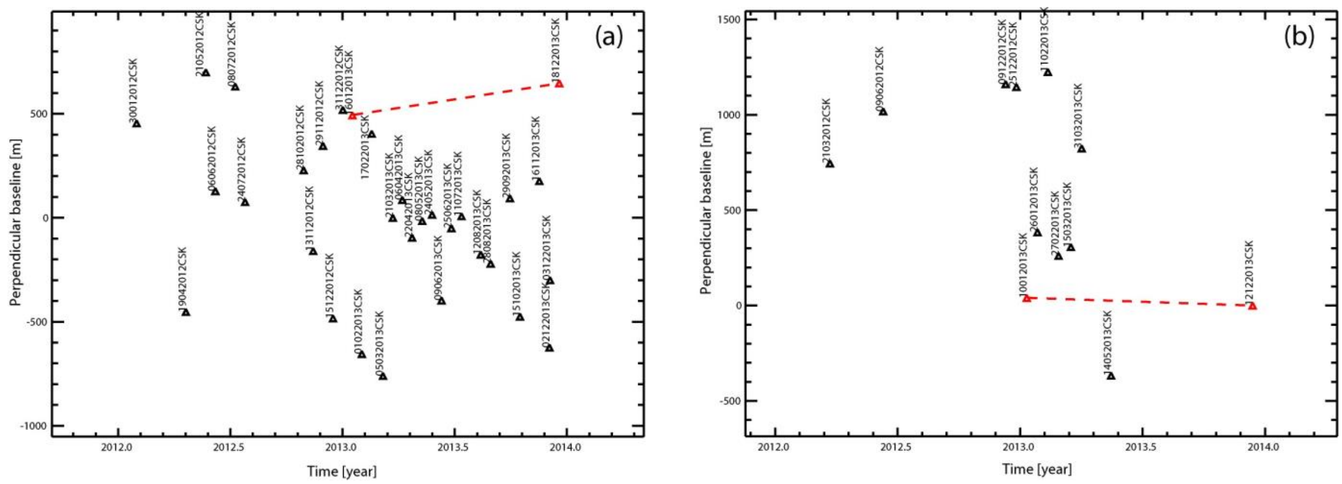
S2. High resolution map of the surface deformation produced by the new Montescaglioso landslide, as identified by field surveys. The moving mass determined the formation of pressure ridges and thrusts for some hundreds of meters, as well as the damming of Fosso Capoiazzo, with consequent formation of several lakes. In particular, the area of the original confluence between the two water lines (Canale Cinque Bocche and Fosso Capoiazzo, see also Fig. 1) was considerably modified, being strongly altered the hydrographic network due to the accumulation of the material pushed from upstream. A further lake was formed at this site, too. The morphological characters observed and mapped indicate that the phenomenon was a translational slide, with main direction of movement towards SW. In its middle-lower portion, because of the obstacle constituted by the body of an ancient paleo-landslide delimited by the two water lines mentioned above, the direction of the main movement changed toward SSW, strongly conditioned by the right flank of the landslide, approximately striking NS.The base map is the WMS 2006 color orto-photomap, downloaded from http://www.pcn.minambiente.it.



S3. DInSAR interferograms relevant to the Montescaglioso landslide area, achieved by exploiting pre- and post-event CSK acquisitions over ascending (a-b) and descending (c-d) orbits. (a) 3 December 2013-18 December 2014 interferogram with perpendicular baseline of about 900 m. (b) 16 January 2013-18 December 2014 interferogram, 155 m of perpendicular baseline. (c) 14 May 2013-12 December 2014 interferogram with perpendicular baseline of 350 m. (d) 10 January 2013-12 December 2014 interferogram, 40 m of perpendicular baseline. The spatial coherence is not preserved due to the amount of surface displacements, resulting in the complete loss of coherence of the DInSAR signal in the areas experiencing the largest deformations. Note also that the loss of coherence in the area near (but outside) the landslide (highlighted by the dashed white ellipse) is generally due to the large temporal and/or spatial baseline values characterizing the available SAR data pairs across the event.



S4. SAR data representation in the temporal/perpendicular baseline plane for the (a) ascending and (b) descending CSK datasets. Dates are in the DDMMYYYY format. The black triangles identify the whole CSK acquisitions, while the red ones, connected with the dashed red lines, correspond to the SAR data pairs used for applying the Pixel Offset technique.



S5 Stereoscopic aerial photographs used to prepare the landslide inventory map of the Montescaglioso study area. The images are available at the website of the Istituto Geografico Militare Italiano (IGMI) (http://www.igmi.org/voli/).

YEAR	STRIP	PHOTOGRAPH	TYPE	SCALE
1947	6	45c, 46c, 47c, 48c, 49c, 45s, 46s, 47s, 48s, 49s	black-and-white	1:24,000
1954	152	6950, 6951, 6952	black-and-white	1:34,000
1972	3bis	5522, 5523, 5524	black-and-white	1:30,000
1989	36	44, 45, 46	black-and-white	1:27,000
1990	31	731, 732, 733	black-and-white	1:36,000
1996	38	90, 91, 92, 93	black-and-white	1:34,000
2003	131	6107, 6108, 6109, 6110	black-and-white	1:30,000
2003	126	6157, 6158, 6159	black-and-white	1:30,000

S6. Aerial photograph taken form helicopter after the landslide. The location of the Hypermarket, as well as of the most damaged buildings (A and B) is also identified.