Dear Editor and Referees,

We wish to thank you for your effort in improving our paper. We agree that several parts of the manuscript needed to be reviewed. In particular we feel that now this work is more incisive and its purpose clearer. This was thanks to your suggestions, especially those relative to cutting unnecessary parts or to better explaining some others.

Following, we resume all the answers to your requests together in this single file because they are tightly linked to each other and we think that in this way they are more understandable.

In order to give informed answer, we preferred to modify the manuscript according to your revisions, although this was not necessary at this stage (this is why we could not upload it yet). In this way, we were able to answer your suggestions not just theoretically but according to what we actually changed in the manuscript.

Best regards on behalf of all co-authors,

Emanuele Intrieri

Answers to S. L. Gariano (Editor)

Dear Authors, both reviewers considered your work good and publishable, after revisions. In particular, they believe that the “technical” parts of the work should be reduced and/or summarized. I agree with them. Thus, I have also some suggestions, listed below:

- Text in rows 61-83 could be largely reduced.

It has been almost entirely deleted (see also answers to Referee #1 and #2).

- Sections 3.1, 3.2, and 3.3 could be reduced.

Section 3.1: the part relative to how interferometric data are made and how they are elaborated has been deleted (see also answers to Referee #1 and #2).

Section 3.2: this has been reduced and a figure has been deleted (see also answers to Referee #1).

Section 3.3: this has been reduced as suggested.

- Figures 4 and 5 could be deleted.

They have been deleted from section 4. For reference, in the new version their numbering was no more 4 and 5 but 3 and 4.

- Finally, I suggest reviewing the abstract by adding more precise information about the method described in the paper and the obtained results.

Sincerely, Stefano Luigi Gariano

Thank you for your observation. In fact we probably missed to properly convey the message of our paper. This might have created confusion in some of the comments of the two referees concerning the fact that our aim and obtained results are not the monitoring data themselves, rather the procedures employed to obtain them. Therefore we changed the final part of the abstract ad replaced it with the following sentence:

“The aim of this paper is to show how logistic issues linked to advanced monitoring techniques such as big data transfer and storing, can be dealt with, compatibly with an early warning system. Therefore, we focus on the interaction between an areal monitoring tool (a ground-based interferometric radar) and the DCPC. By converting complex data into ASCII strings and through appropriate data cropping and average, and by implementing an algorithm for line of sight correction, we managed to reduce the data daily output without compromising the capability of performing”.

Answers to Anonymous Referee #1

General comments

The paper presents a procedure for the integration of GB-InSAR data within an early warning integrated system for risk prevention for a critical infrastructure (A16 highways connecting Naples to Bari in southern Italy). The use of GBInSAR for landslide monitoring is not new in the scientific literature, although not yet standardized, so its use in EWS is certainly of interest to the community of landslide researchers. The used language is correct and readable. However, some changes are suggested before publication on NHESS journal. The weak point is that the current version of the paper appears as a “technical note” rather than an original research article. Indeed, the Authors provide plenty of details concerning the LEWIS system (that is not central in the work) and both the installation and set-up of GB-InSAR tool but, on the other hand, the interpretation of the results and the adoption of thresholds for early warning purposes based on GB-InSAR data is not given the same room and relevance. So, given the timely topic addressed and the potential of these kind of applications, Authors are invited to better balance different parts of the paper to improve the overall quality and readability of the work for the typical audience of NHESS. Some suggestion are provided hereafter.

As the Editor highlighted, technical note are not available for this Journal. The paper has been balanced following the suggestions furnished in the following comments of the reviewer. In particular, we have better explained the method used here to set thresholds but, since the setting of thresholds is not the objective of the paper, we have also explained that the system is open and different methods can be implemented as well. Furthermore, the part concerning LEWIS has been reduced and a figure removed, in order to better balance the topic of the paper.

Specific comments

Lines 55 to 83 provide too many details anticipating the technical descriptions that are expected instead in section 3 or 5. Please remove from here.

This paragraph has been in part moved in paragraph 5 and in large part deleted since it mainly anticipated concepts more deeply described in paragraph 5.

In section 3.1 the description of LEWIS should be reduced since the Authors already refer to the published work of Costanzo et al. (2016).

The section containing information about LEWIS (3.2) has been reduced as suggested and in particular a figure has been removed (Fig. 2). Only the parts that are important to allow the reader to easily understand the following sections have been kept.

In section 6, please better clarify how GB-InSAR data interpretation and analysis contribute to fix thresholds for early warning.

Technical corrections: - In the abstract do not use future tense (line 29) –

Done

Lines 76, 78: change “where” in “were”.

This part has been removed.

- Figure 1: change the shaded fonts because they are not readable

The font has been changed and the shaded box now have a solid colour.

- Figure 2: increase the font size.

This figure has been removed.

- Lines 251, 252: use the past tense.

Done.

- Line 327: add references to:

- Cascini et al., 2010 (for first maps of DInSAR data projected along the steepest slope direction). Cascini L., Fornaro G., Peduto D. (2010). Advanced low- and full-resolution DInSAR map generation for slowmoving landslide analysis at different scales. Engineering Geology, 112 (1-4), 29-42, doi:10.1016/j.enggeo.2010.01.003.;

and to Cascini, L., Peduto, D., Pisciotta, G., Arena, L., Ferlisi, S., and Fornaro, G. (2013): The combination of DInSAR and facility damage data for the updating of slow-moving landslide inventory maps at medium scale, Nat. Hazards Earth Syst. Sci., 13, 1527-1549, doi:10.5194/nhess-13-1527-2013, for the map of projectable DInSAR data.

The references to Cascini et al. have been added.

- Line 412: please clarify better to which “friction” you are referring.

We were referring to the friction between vehicles and the tar. Now it is specified in the text.

Answers to Anonymous Referee #2

The authors submitted a work to present the role of GB-InSAR on an integrated system for landslide monitoring. In particular, the early warning system architecture and the data management are treated. The work is referred to the LEWIS project and it is focused on a critical infrastructure in southern Italy (A16 highways). Although the technology here presented is now well-known, the integration with other monitoring technique and the development of EWS are interesting topics. The objectives of the manuscript are clear and the paper covers an area of interest to the journal's readership.

In order to improve the manuscript, I recommend authors to summarize the section with irrelevant details for readers (eg. GB-InSAR features..) focusing on data analysis and interpretation, also by adding some displacement time series.

The sections highlighted by the referee have been heavily reduced and 3 figures have been removed in total. Concerning the time series, we have not included them since these are not really meaningful. In fact, the slope did not experience significant movements and the growth of the vegetation produces noise that concealed the slightest deformations, which did not exceed the instrumental resolution (less than one millimiter per day). On the other hand, displacement maps (now figure 7) have been included, in order to show some displacement data nonetheless and to show that displacements were negligible. Indeed, as you rightly pointed put, the use of GB-InSAR for landslide monitoring is not new and it was not the aim of our paper. Our scope was to explain a procedure to overcome some logistic issues encountered in an early warning system, such as big data. We have added to better explain our scope in the abstract and in the introduction. They are reported below.

In the abstract: "The aim of this paper is to show how logistic issues linked to advanced monitoring techniques such as big data transfer and storing, can be dealt with, compatibly with an early warning system. Therefore, we focus on the interaction between an areal monitoring tool (a ground-based interferometric radar) and the DCPC. By converting complex data into ASCII strings and through appropriate data cropping and average, and by implementing an algorithm for line of sight correction, we managed to reduce the data daily output without compromising the capability of performing."

In the introduction: "One of the main drawbacks of advanced instruments such as GB-InSAR is how to handle the large data flow deriving from continuous real-time monitoring. The issue is to reduce the capacity needed for analyzing, transmitting and storing big data without losing important information. The main feature of this paper is indeed the management of monitoring data in order to filter, correct, transfer and access them compatibly with the needs of an early warning system."

In addition, it is really important to improve the conclusions, also by focusing on data integration for EWS.

Thank you for pointing out this issue. We improved the conclusions by better explaining the possible usefulness of our paper with reference to similar situations. Unfortunately, we do not have data from other instruments; in fact, all the monitoring devices were independent and the integration was only needed at a higher level, when monitoring data and results from modeling were finally integrated and a risk assessment was possible. These aspects are already treated in other paper cited in the manuscript (Versace et al., 2012; Costanzo et al., 2015; 2016). In this paper, we only deal with the interaction between GB-InSAR and the DCPC. In fact, what happen next (e.g. data integration between GB-InSAR and other instruments) falls out of our interest and detailed knowledge.

Following, some specific comments and minor points to improve the text:

- Page 2, row 56: please replace "aerial" with "spatial"

Done.

- Page 2, rows 56-57: please replace "The installation was in an area where the only internet connection available 57 was 3G" with "the monitoring area was covered by a 3G mobile telecommunication networks"

This sentence has been changed as suggested and it is now at the beginning of section 5, following the suggestion of referee #1.

- Page 2, rows 61-83: these lines are very specific and of little interest to readers. Please consider deleting these lines or inserting them in Section 3.3.

They have been deleted and only in small part moved.

- Page 2, row 76: please change “where” with “were”

This part has been removed from the paper.

- Page 3, row 86: please change "ground-based interferometric synthetic aperture radar" with "Ground-Based Interferometric Synthetic Aperture Radar (GB-InSAR)"

We have now changed this.

- Section 3.1: this section appears too long. Please consider reducing sentences and adding a table with the technical specifications of equipment used (eg. Frequency, Bandwidth, Range and Cross-range resolution, etc.).

Thank you for this comment. In fact this part was mostly a repetition and has been largely reduced. We also remove the part explaining the technical specifications of the equipment, since this information can be found in the literature cited in the paper and is not fundamental for our purpose.

- Section 4: please add more geological information (eg. materials involved) to better frame the area under study.

Now we have explained that “The lithologies outcropping in this area are Pliocene-Quaternary clay, clayey marlstones, and more recent (Holocene) terraced alluvial sediments (from clay to gravel). The landslides shown in Figure 2 are all located in clay or clayey marlstones”.

- Page 8, row 250: please add space before "These"

Done.

- Fig. 1: please improve the quality of figure

Now the text is bolder and the boxes are no longer filled with a gradient but with a solid color.

- Fig. 3: please increase the font size

The font size has been increased.

- Fig. 8: please insert the location of GB-InSAR instrument installed.

You are right. The yellow asterisk in the left of the images represents the location of the GB-InSAR. This is now specified in the caption of the image.

Big data managing in a landslide Early Warning System: experience from a ground-based interferometric radar application

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Keywords: early warning system; slope instability; big data; monitoring; landslide; risk management; ground-based interferometric radar

1 Abstract

A big challenge in terms or landslide risk mitigation is represented by the increasing of the resiliency of society exposed to the risk. Among the possible strategies to reach this goal, there is the implementation of early warning systems. This paper describes a procedure to improve early warning activities in areas affected by high landslide risk, such as those classified as Critical Infrastructures for their central role in society.
This research is part of the project "LEWIS (Landslides Early Warning Integrated System): An Integrated System for Landslide Monitoring, Early Warning and Risk Mitigation along Lifelines".
LEWIS is composed of a susceptibility assessment methodology providing information for single points and areal monitoring systems, a data transmission network and a Data Collecting ~~A~~and Processing Center (DCPC), where readings from all monitoring systems and mathematical models converge and which sets the basis for warning and intervention activities.

The aim of this paper is to show how logistic issues linked to advanced monitoring techniques such as big data transfer and storing, can be dealt with, compatibly with an early warning system. ~~In this paper~~Therefore, we ~~will~~ focus on the interaction between an areal monitoring tool (a ground-based interferometric radar) and the DCPC. By converting complex data into ASCII strings and through appropriate data cropping and average, and by implementing an algorithm for line of sight correction, we managed to reduce the data daily output without compromising ~~, and how issues such as big data transfer,~~the capability of performing~~ real-time warning, line of sight correction and data validation in emergency conditions have been dealt with~~.

2 Introduction

Urbanization, especially in mountain areas, can be considered a major cause for high landslide risk because of the increased exposure of elements at risk. Among the elements at risk, important communication routes, such as highways, can be classified as Critical Infrastructures (CIs), since their rupture can cause chain effects with catastrophic damages on society (Geertsema et al 2009; Kadri et al. 2014). On the other hand, modern society is more and more dependent from CIs and their continuous efficiency (Lebaka et al., 2016), and this has risen their value over the years. The result is a higher social vulnerability in the face of loss of continuous operation (Kröger, 2008). The main objective was to improve the social preparedness to the growing landslide risk, according with the suggestions of several authors (Gene Corley et al., 1998; Baldridge et al., 2011; Urlainis et al. 2014; 2015). This led to the development of several approaches and frameworks for increasing the resiliency of society exposed to the risk (Kröger, 2008; Cagno et al., 2011 and references therein). The resiliency policy of course involves prevention activities but also, and more importantly, those activities needed to maintain functionality after disruption (Snyder and Burns, 2009) and to promptly alert incoming catastrophes in order to protect people and prepare for a possible damaging of the endangered CI. Among these activities, the implementation of integrated landslides early warning systems (*i.e.* LEWIS, Versace et al., 2012; Costanzo et al., 2016) reveals its increasing importance.

In this context, the methodology described in this paper has been conceived; it has been tested and validated on a portion of an Italian highway, affected by landslides and selected as case study: it is located in Southern Italy, along a section of the A16 highway, an important communication route that connects Naples to Bari where a ground based interferometer (GB-InSAR) has been installed on the test site, in order to obtain ~~aerial~~spatial monitoring data.

One of the main drawbacks of advanced instruments such as GB-InSAR is how to handle the large data flow deriving from continuous real-time monitoring. The issue is to reduce the capacity needed for analyzing, transmitting and storing big data without losing important information. The main feature of this paper is indeed the management of monitoring data in order to filter, correct, transfer and access them compatibly with the needs of an early warning system.~~.~~

~~A ground based interferometer (GB-InSAR) has been installed on the test site, in order to obtain aerial monitoring data. The installation was in an area where the only internet connection available was 3G, with a limit of 2 gigabyte data transfer per month. Nevertheless, these data could be managed thanks to the implemented data transmission network and Data Collecting and Processing Center (DCPC), organized taking into account both the internet network problems and the big amount of data produced by the interferometer.~~

~~Interferometric data are indeed complex numbers, organized in a matrix where each pixel contains both phase and amplitude information of the backscattered signal (Bamler and Hartl, 1998; Antonello et al., 2004); the radar employed produced a 1001x1001 complex matrix (corresponding to ~7 megabytes) every 5 minutes. Therefore, there was the need to reduce the massive data flow produced by the radar. For this reason data were locally and automatically elaborated in order to produce, from a complex matrix, a simple ASCII grid containing only the pixel by pixel displacement value, which is derived from the phase information. Then, since interferometry only measures the displacement component projected along the radar line of sight, data needed to be re-projected. This was performed by dividing the ASCII grid by a correction matrix, where every~~

~~element of the matrix was the percentage of the actual displacement that was measurable by the radar; such percentage can be obtained with trigonometrical arguments knowing the position of the radar and the direction of movement of the landslides (which, in our case, corresponded with the slope direction) thus enabling the calculation of the radar line of sight.~~

~~To further reduce the size of the grids, matrixes where cropped in order to contain only those pixels where relevant information could be extracted.~~

~~The ASCII grids where also averaged to reduce noise, so 8-hours and 24-hours averaged grids were obtained. According to the early warning procedures that were defined, during periods characterized by low or null slope movement, only 8-hours and 24-hours data where transferred, together with the last displacement measurement of a reduced number of control points.~~

~~The transfer was performed after transforming the grids into strings and by sending them through a middleware to the Data Acquisition and Elaboration Centre, where control points displacement values where compared with warning thresholds and the grids where projected on a GIS environment as 2D displacement maps.~~

3 Materials and methods

3.1 GB-InSAR

The ~~g~~Ground-~~b~~Based ~~I~~interferometric ~~S~~synthetic ~~a~~Aperture ~~R~~radar (GB-InSAR) is composed of a microwave transceiver mounted on a linear rail (Tarchi et al., 1997; Rudolf et al., 1999; Tarchi et al., 1999). The system used is based on a Continuous Wave – Stepped Frequency radar, which moves along the rail at millimeter steps, in order to perform the synthetic aperture; the longer the rail the higher the cross-range resolution. The microwave transmitter produces, step-by-step, continuous waves around a central frequency, which influences the cross-range resolution and determines the interferometric sensitivity i.e. the minimum measurable displacement, usually largely smaller than the corresponding wavelength.

~~The installation was in an area where the only internet connection available was 3G, with a limit of 2 gigabyte data transfer per month. Nevertheless, these data could be managed thanks to the implemented data transmission network and Data Collecting and Processing Center (DCPC), organized taking into account both the internet network problems and the big amount of data produced by the interferometer.~~

~~Interferometric data are indeed complex numbers, organized in a matrix where each pixel contains both phase and amplitude information of the backscattered signal (Bamler and Hartl, 1998; Antonello et al., 2004); the radar employed produced a 1001x1001 complex matrix (corresponding to ~7 megabytes) every 5 minutes. Therefore, there was the need to reduce the massive data flow produced by the radar. For this reason data were locally and automatically elaborated in order to produce, from a complex matrix, a simple ASCII grid containing only the pixel by pixel displacement value, which is derived from the phase information. Then, since interferometry only measures the displacement component projected along the radar line of sight, data needed to be re-projected. This was performed by dividing the ASCII grid by a correction matrix, where every element of the matrix was the percentage of the actual displacement that was measurable by the radar; such percentage can be obtained with trigonometrical arguments knowing the position of the~~

~~radar and the direction of movement of the landslides (which, in our case, corresponded with the slope direction) thus enabling the calculation of the radar line of sight.~~

~~To further reduce the size of the grids, matrixes where cropped in order to contain only those pixels where relevant information could be extracted.~~

~~The ASCII grids where also averaged to reduce noise, so 8 hours and 24 hours averaged grids were obtained. According to the early warning procedures that were defined, during periods characterized by low or null slope movement, only 8 hours and 24 hours data where transferred, together with the last displacement measurement of a reduced number of control points.~~

~~The transfer was performed after transforming the grids into strings and by sending them through a middleware to the Data Acquisition and Elaboration Centre, where control points displacement values where compared with warning thresholds and the grids where projected on a GIS environment as 2D displacement maps.~~

The radar produces complex radar images containing the information relative to both phase and amplitude of the microwave signal backscattered by the target (Bamler and Hartl, 1998; Antonello et al., 2004). The amplitude of a single image provides the radar reflectivity of the scenario at a given time, while the phase of a single image is not usable. The technique that enables to retrieve displacement information is called interferometry and requires the phase from two images. In this way, it is possible to elaborate a displacement map relative to the elapsed time between the two acquisitions.

The main added value of GB-InSAR is its capability of blending the boundary between mapping and monitoring, by computing 2D displacement maps in near real-time. The use of this tool to monitor structures, landslides, volcanoes, sinkholes is largely documented (Calvari et al., 2016; Di Traglia 2014; Intrieri et al., 2015; Bardi et al., 2016, 2017; Martino and Mazzanti, 2014; Severin, 2014; Tapete et al., 2013), as well as for early warning and forecasting (Intrieri et al., 2012; Carlà et al., 2016a; 2016b; Lombardi et al., 2016).

GB-InSAR systems probably reveal their full potential in emergency conditions. They are transportable and only require from few tens of minutes to few hours to be installed (depending on the logistics of the site). Moreover, they ~~are able to~~can detect "near-real time" area displacements, without accessing the unstable area, 24h and in all weather conditions (Del Ventisette et al., 2011; Luzi, 2010; Monserrat et al., 2014). On the other hand, some limitations reduce the GB-InSAR technique applicability: first of all the scenario must present specific characteristics in order to reflect microwave radiations, maintaining high coherence values (Luzi, 2010; Monserrat et al., 2014); only a component of the real displacement vector can be identified (i.e. the component parallel to the sensor's line of sight); maximum detectable velocities are connected to the time that the system needs to obtain two subsequent acquisitions. Sensors need power supply that, for long term monitoring, cannot be replaced by batteries, generators or solar panels.

With the specific aim of performing an early warning system, data acquired *in situ* must be sent automatically to a "control center" where they are integrated in a complete early warning system procedure (Intrieri et al., 2013). In this sense, another main limitation is represented by the necessity to transfer a high quantity of data, whose weight has to be reduced to the minimum, in order to reduce the load on transmission network.

The employed system is a portable device designed and implemented by the Joint Research Center (JRC) of the European Commission and its spin-off company Ellegi-LiSALab (Tarchi et al., 2003; Antonello et al., 2004). ~~The linear rail is 210 cm long, allowing a synthetic aperture of maximum 180 cm. It is easily transported by a normal motorized vehicle but its length is enough to obtain high cross-resolution images, also at a distance from the scenario the can reach more than 1 km. The transmitter and receiver move on the rail on a specific support, which can be tilted in order to~~to ~~direct the microwave radiation as much as possible parallel to the displacement direction. The power base represents the control center of the system; it contains a personal computer that manages the definition of input parameters used in the acquisition phase and a UPS (Uninterruptible Power Supply) to guarantee constant electric supply; it also enables data elaboration and storage, being equipped with two boards increasing the memory to 1.8 TiB. The employed system needs 850 W, 230 VAC and 50 Hz as power supply. The integrated UPS guarantees the continuity of the electric supply in case of necessity, for a period of maximum 12 hours after the power cut. The total weight of the instrument is 95 kg, equally distributed over the different components (power base with UPS and boards, transceiver, linear rail).~~

3.2 Early warning system architecture

Morphological features, hydrogeological factors and sudden rainfall can cause ~~different~~ diverse types of movements or fall of earthy and rock materials. The unpredictability and diversity of these events make structural interventions often inappropriate to reduce the related risk, and real-~~-~~time monitoring network difficult to implement.

In the last decade, Wireless Sensor Networks (WSNs) have been largely used in various fields. A significant increase in the use of WSN, due to their simplicity, low cost of installation, manufacturing and maintenance, has been recorded in the framework of environmental monitoring applications (Intrieri et al., 2012; Liu et al., 2007; Yoo et al., 2007). ~~Different~~ Distinct types of sensor nodes of these networks, distributed with high density in the monitored areas, send environmental information to the concentrators nodes, generating a considerable amount and a wide variety of collected data. Due to the significant growth of data volumes to be transferred, the WSN require flexible ad-hoc protocols, able to respect constraints related to energy consumption management (Hadadian and Kavian, 2016; Khaday et al., 2015; Parthasarathy et al., 2015). In particular, many protocols have been developed that offer data aggregation patterns to optimize the sensor nodes battery life (Kim et al., 2015) or sleep/measurement/data transfer cycles to minimize the energy consumption (Fei et al., 2013; Venkateswaran and Kennedy, 2013).

LEWIS (Costanzo et al., 2016) uses heterogeneous sensors, distributed in the risk areas, to monitor the several physical quantities related to landslides. The measured data, through a telecommunications network, flow into the Data Collecting ~~A~~and Processing Center (DCPC), where, using suitable mathematical models for the monitored site, the risk is evaluated and eventually the state of alert for mitigation action is released (Figure 1).

The system, through a modular architecture exploiting a telecommunication network (called LEWARnet) based on an ad-hoc communication protocol and an adaptive middleware, has a high flexibility, which allows for the use of different interchangeable technological solutions to monitor the parameters of interest.

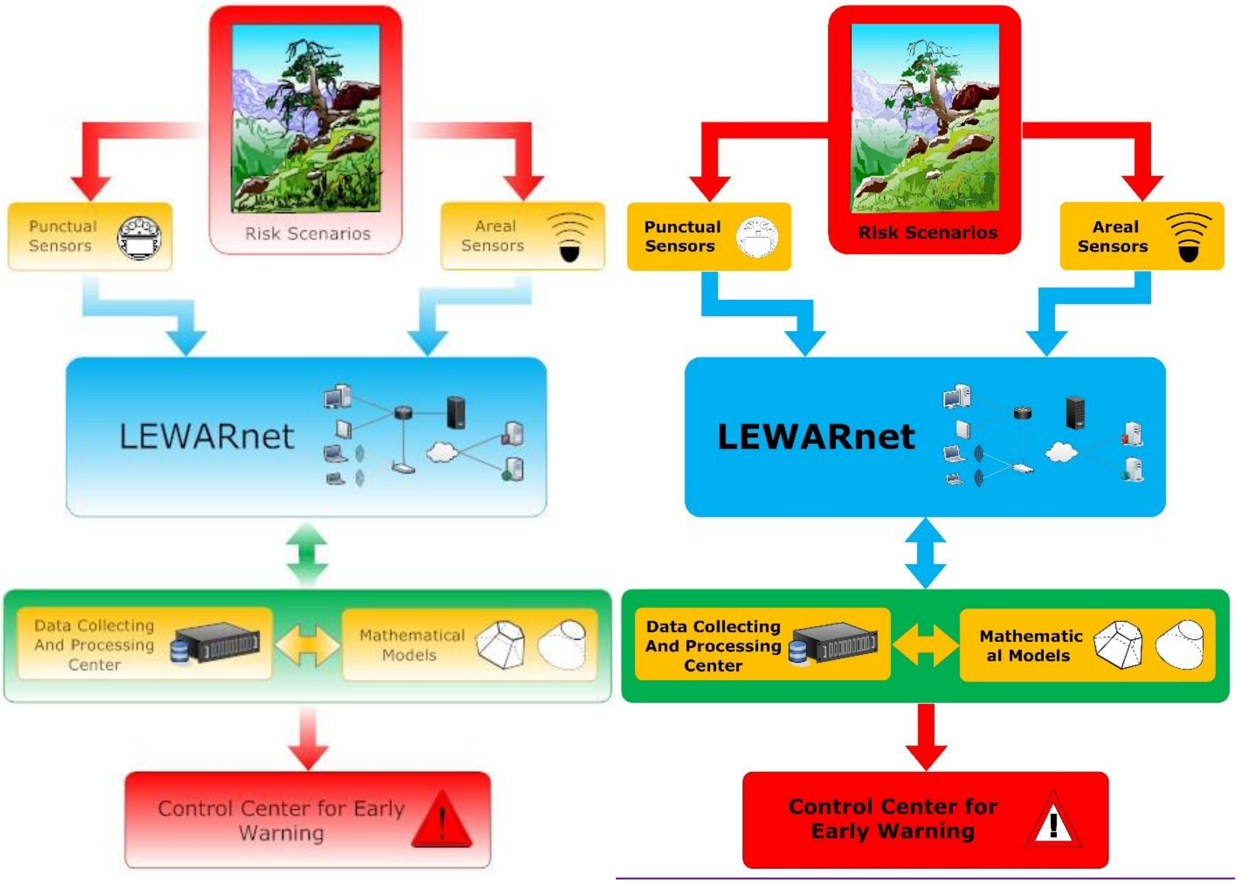

Figure 1. LEWIS architecture.

~~The telecommunication network has been designed and implemented within the Microwave Laboratory of the University of Calabria.~~

~~The areas to be monitored have been divided into geomorphological units, indicated as GU. Each GU is then subdivided into more heterogeneous sensors subnets.~~

~~For this purpose, each GU contains a concentrator node, called first level Sink, which has the purpose of coordinating the sensors or any sub-network of sensors and collect the measurements from them to transmit the data to the DCPC. Each sub-network is coordinated by a second level Sink node, connected to the first level Sink through a short-range wireless connection (eg. ZigBee, Bluetooth).~~

~~The network architecture can be schematized as shown in Figure 2.~~

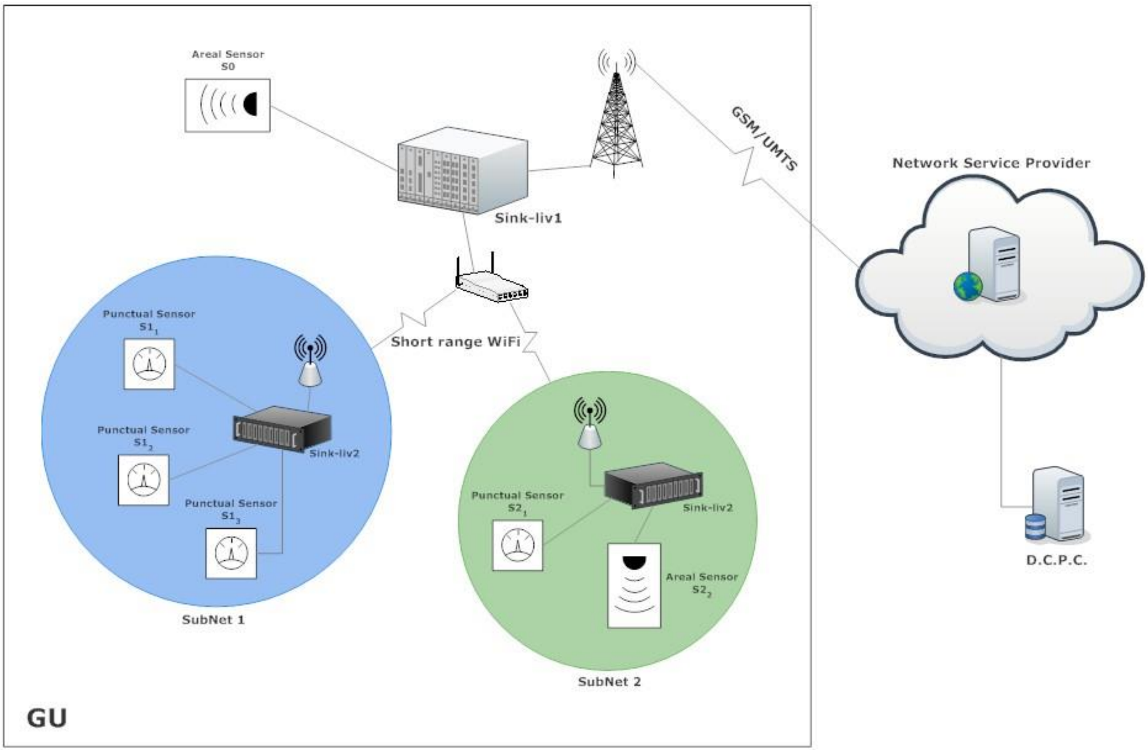

Figure 2. LEWARnet architecture.

The network has been equipped with both single point sensors as well as area sensors, and the sub-networks may include the use of a single type of these or both. The present paper addresses a sub-network comprising an area sensor, the GB-InSAR.

The different sensors types generate asynchronous traffic, thus imposing the adoption of an ad-hoc transmission protocol. This can support an asynchronous transmission mode to the DCPC, and it is equipped with message queues management capacity to reconstruct historical data series, between two connection sessions, in case of null or partial transmission. This operation mode requires the presence of a software architecture that operates as a buffer, acting as an intermediary or as middleware (LEWARnet), between the data consumer (DCPC) and the data producers (sensors and sub-networks of sensors).

The developed middleware also monitors the processes of transmission and data acquisition, recognizing the activity status of the sensors and that of the DCPC, and integrating encryption and data compression functions.

A detail description of LEWIS can be found in Costanzo et al. (2015; 2016).

3.3 Data Collecting and Processing Center (DCPC)

The management of information flows, the telematic architecture and the services for data management are entrusted to the DCPC.

The DCPC has been designed and performed according to a complex hardware and software system, able to ensure the reliability and continuity of the service, providing advance information of possible dangerous situations that may occur.

In the research project, the DCPC has to ensure the continuous exchange of information among monitoring networks, mathematical models and the Command and Control Center (CCC), that is responsible for emergency management and decision making.

~~The design and implementation of procedures for the exchange of information from the monitored sites to the CCC was built according to persistent and stable communication protocols, that are suitable for hardware/software architecture of monitoring devices, for models and for CCC.~~

Data flow from the monitoring network was managed according to a communication protocol, implemented by the DCPC, and named AqSERV. AqSERV was designed considering the heterogeneity of devices of monitoring and transmission networks (single point and area sensors) and the available hardware resources (microcontrollers and/or industrial computers). AqSERV was devised to link DCPC database (named LEWISDB) to the monitoring networks, after validation for the authenticity of the node that connects to the center. Data acquisition, before the storage in the database, is validated both syntactically and according to the information content. The procedures for extraction of the information content and validation have been realized differently for single point and area sensors: the latter require a more complex validation, as they work in a 2D domain.

The complete management of the monitoring networks by DCPC has been realized through specific remote commands, sent to individual devices via AqSERV, to reconfigure the acquisition intervals or to activate any sensor, depending on the natural phenomena occurring in real time.

~~The acquired and validated data are then accessible for the mathematical models through a further service, created ad hoc, which publishes all the acquisitions by sensors on a remote server for sharing.~~

The configuration of monitoring networks, composed by devices and sensors, of communication protocol used by each network, and of rules for extraction and validation of information content is carried out through a web application that allows for the management of the ~~whole~~ entire system by the users.

~~Besides the configuration, the application has been configured to automatically create the tables of interest; automation of the process permits to reduce the acquisition time and possible human errors.~~

The real-time search for acquisitions is carried out through a WebGIS, specifically designed for WSNs, but that can be easily extended to classic monitoring networks.

The WebGIS was designed according to the traditional web architecture, client-server, by using network services which are web mapping oriented:

- web server for static data;
- web server for dynamic data;
- server for maps;
- database for the management of map data.

~~The static layers provided by the WebGIS are the results produced by geological studies for the identification of event scenarios: geological map, geomorphological map, map of event scenarios. The dynamic layers are the acquisitions in real time by the sensors.~~

~~A DCPC operator can consult the information provided by each layer via a standard web browser verifying the performance of the event precursors and any anomalies in acquisitions.~~

4 Test site

The test site chosen to experiment the integrated system is located in Southern Italy, along a section of the A16 highway, an important communication route that connects Naples to Bari (Figure 2).

The A16 selected section develops in SW-NE direction, along the Southern Italian Apennine, in correspondence with the valley of the Calaggio Creek, between the towns of Lacedonia (Campania Region) and Candela (Puglia Region).

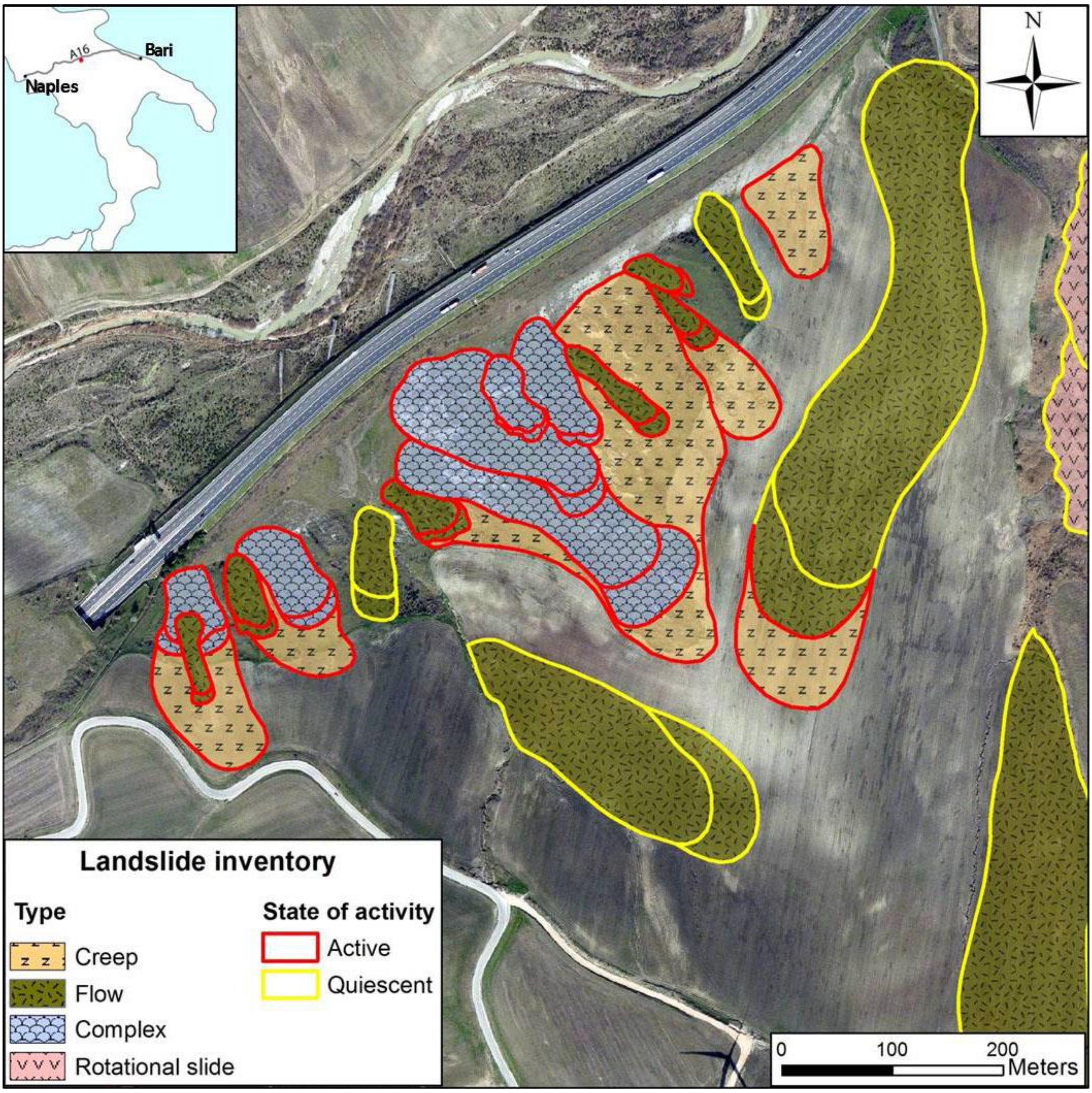

Figure 2. Landslides detected through field survey along the monitored section of A16 highway.

The area is tectonically active, but the landscape, characterized by gentle slopes, is mostly influenced by lithologic factors ~~(the strong presence of clayey sediments)~~ rather than by tectonics. The lithologies outcropping in this area are Pliocene-Quaternary clay, clayey marlstones, and more recent (Holocene) terraced alluvial sediments (from clay to gravel). The landslides shown in Figure 2 are all located in clay or clayey marlstones.

The highway runs on the right flank of the Calaggio Creek at an altitude between 300 and 400 m a.s.l.; the section of interest represents an element at risk in the computation of landslide risk assessment, due to the presence of unstable areas which can potentially affect the communication route (Figure 2). These unstable areas mainly involve clayey superficial layers.

On 1st July 2014, the GB-InSAR system ~~has~~ was~~been~~ installed on the test site. The location of the installation point ~~has been~~was selected taking into account the view of the unstable area and the distance from the power supply network. A covered structure was built ~~in order~~ to protect the system from atmospheric agents and possible acts of vandalism, in the perspective of a long-~~ ~~term monitoring~~ (Figure 3)~~.

~~**Figure 3. Pictures of the construction of the covered structure and installation of the GB-InSAR.**~~

The transmission network was provided by a GSM modem, exploiting the 3G network. In addition to the PC integrated in the GB-InSAR power base, a further external PC was exclusively employed for data post elaboration and transmission.

The system acquired from the beginning of July 2014 until the end of July 2015.

The installation location allowed the system to detect an area between 40 and 400 meters far from the its position in range direction, and about 360 m wide in the azimuth direction. These values, coupled with a 40° vertical aperture of the antennas, allowed operators to detect an area of about 360 m x 360 m~~ (Figure 4)~~.

Figure 4. Field of view of the slope from the GB-InSAR installation point.

5 Data management

The most relevant matter of this monitoring was not as much related to the detection of landslide movements threatening the highway, as to how a long--term monitoring performed with an instrument providing huge amounts of data could have been run without resorting to large hard drives nor to fast internet connections. For this reason an appropriate data management (Figure 6) was developed.In fact, the monitoring area was covered by a 3G mobile telecommunication networksthe installation was in an area where the only internet connection available was 3G, with a limit of 2 gigabyte data transfer per month and there was the need to reduce the massive data flow produced by the radar.

For this reason, an appropriate data management (Figure 3) was developed and is here described.

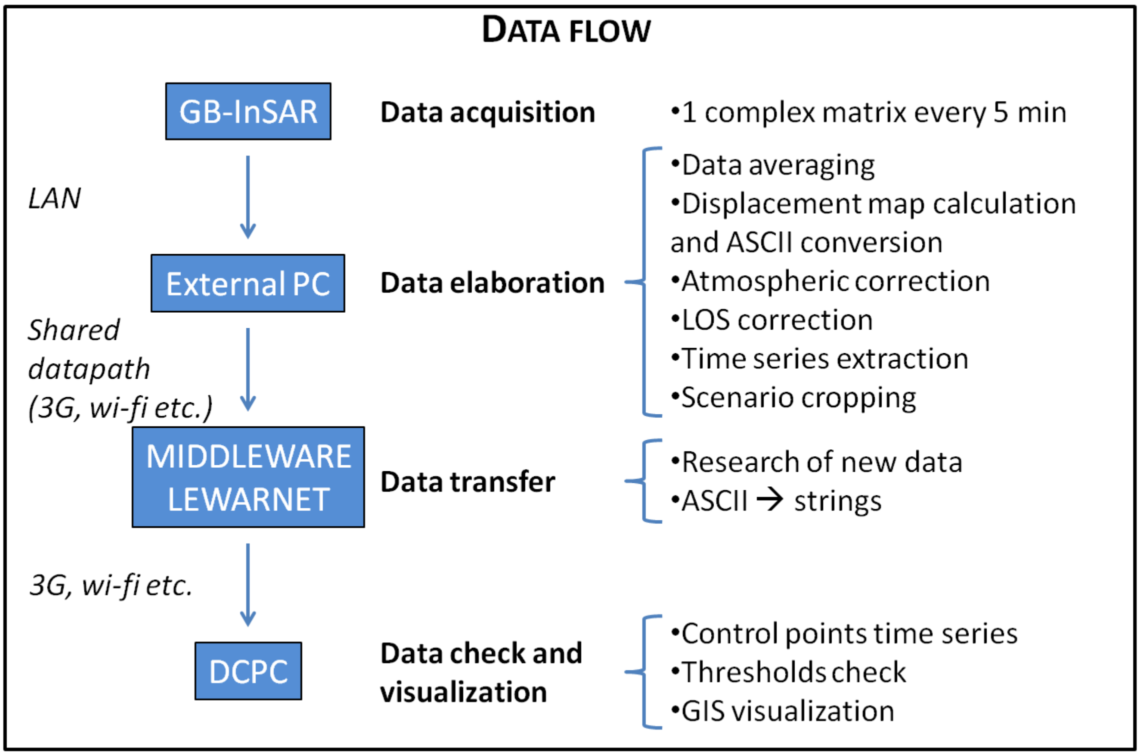

Figure 3. Diagram showing the complete data flow from acquisition to final visualization.

5.1 Data acquisition

The GB-InSAR employed produced a single radar image, consisting in a 1001x1001 complex matrix, every 5 minutes. Each one is around 8 Megabytes large, resulting in more than 2 Gigabytes of data produced every day.

This amount of data represented an issue for both store capacity and data transmission.

5.2 Data elaboration

After being acquired, data were then transferred through LAN connection to the external PC implementing a dedicated Matlab script locally performing the actions described as follows.

5.2.1 Data averaging

In order to reduce the noise normally affecting radar data (especially in vegetated areas), the images acquired every 5 minutes were also averaged using all data of the previous 8 and 24 hours. Then images averaged on 24 hours have been used to calculate daily displacement maps, every 8 hours to create 8h displacement maps and non-averaged images to calculate 5 minutes displacement maps. These time frames have been selected based on the characteristics of the slope movements and signal/noise ratio in the investigated area.

Averaging is also a mean to make a good use of a high data frequency, since it enables to reduce the memory occupied in the database as an alternative to their direct elimination.

5.2.2 Displacement map calculation and ASCII conversion

Each radar image can be represented as in Eq.1:

$$S_n = A_n \, exp(j\varphi_n) \quad (1)$$

where A_n is the amplitude of the n^{th} image, φ_n its phase and $j = (-1)^{1/2}$ is the imaginary unit. The displacement Δr occurred in the time period between the acquisition of S_1 and S_2 has been calculated with the following (Eq.2):

$$\Delta r = (\lambda/4\pi) \cdot \Delta\varphi \quad (2)$$

where λ is the wavelength of the signal and

$$\Delta\varphi = \varphi_1 - \varphi_2 \quad (3)$$

can be derived from:

$$S_3 = S_1 \, S_2^* = A_1 A_2 \, exp[j(\varphi_1 - \varphi_2)] \quad (4)$$

As a result, an ASCII file, only containing the information relative to the displacement for each pixel, was obtained.

5.2.3 Atmospheric correction

One of the major advantages of GB-InSAR is the capability to achieve sub-millimeter precision. However, this can be severely hampered by the variations of air temperature and humidity, especially when long distances are involved. Usually, atmospheric correction is performed by choosing one area considered stable, taking into account that every displacement value different from 0 is due to atmospheric noise and assuming that this offset is a linear function of the distance. Based on this relation all the displacement map is corrected. In our case the whole scenario has been selected and then only the potential unstable zones and those with a weak or incoherent backscattered signal were removed. The remaining areas were then considered stable and therefore were used for calculating the atmospheric effects. This results in a larger correction region that enables a statistical correlation between the atmospheric effects and the distance and therefore the calculation of a site-specific regression function that may not necessarily be linear (Figure 4).

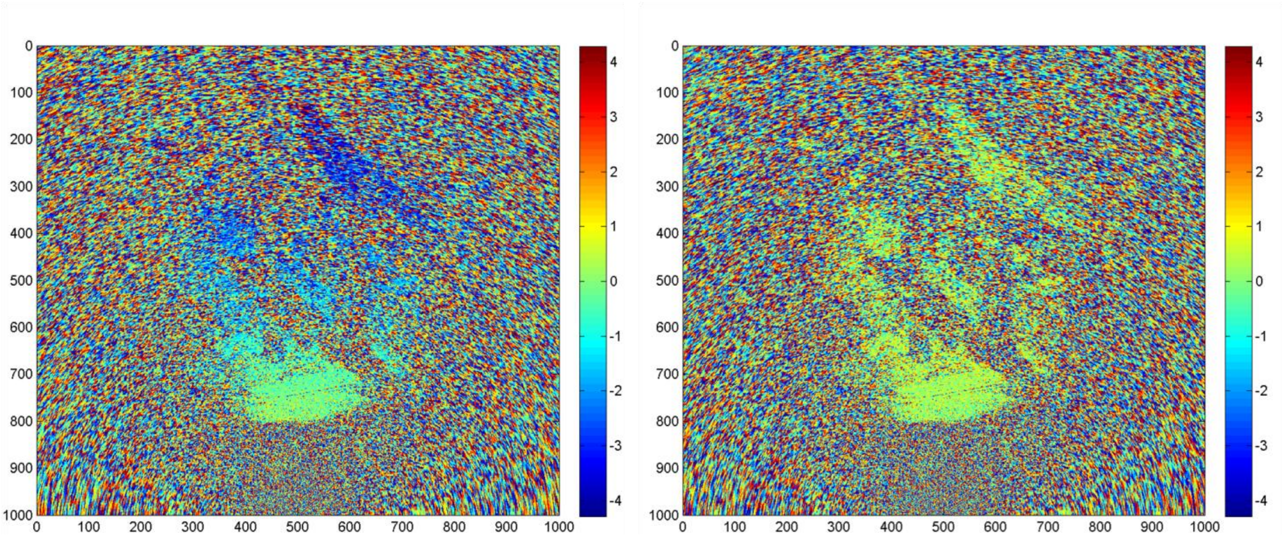

Figure 4. The color bar is expressed in mm; green indicates stable pixels, while blue and red respectively movement toward and away from the GB-InSAR. Left: raw interferogram showing artificial displacement increasing linearly with distance (as typical of atmospheric noise). Right: the same interferogram after the atmospheric correction.

5.2.4 Line of sight correction

The availability to detect only the LOS (Line Of Sight) component of the displacement vector represents one of the main limitations of the GB-InSAR technique. A method to partially overcome this limitation has been applied in this paper, following the procedure described in Colesanti & Wasowski, 2006 and later in Bardi et al. 2014 and 2016. Other methods have been employed by Cascini et al. (2010; 2013).

Assuming the downslope direction as the most probable displacement path, radar data have been projected on this direction. Input data as the angular values of *Aspect* and *Slope* have been derived from the *Digital Terrain Model* (DTM) of the investigated area; furthermore, azimuth angle and incidence angle of the radar LOS have been obtained.

After calculating the direction cosines of LOS and Slope (respectively functions of azimuth and incidence angles and aspect and slope angles) in the directions of Zenith (Z_{los}, Z_{slope}), North (N_{los}, N_{slope}) and East (E_{los}, E_{slope}), the coefficient C is defined as follow (Eq. 5):

$$C = Z_{los} x Z_{slope} + N_{los} x N_{slope} + E_{los} x E_{slope} \quad (5)$$

C represents the percentage of real displacement detected by the radar sensor (Figure 5A).

The real displacement (D_{real}) is defined as the ratio between the displacement recorded along the LOS (D_{los}) and the C value (Figure 5 B).

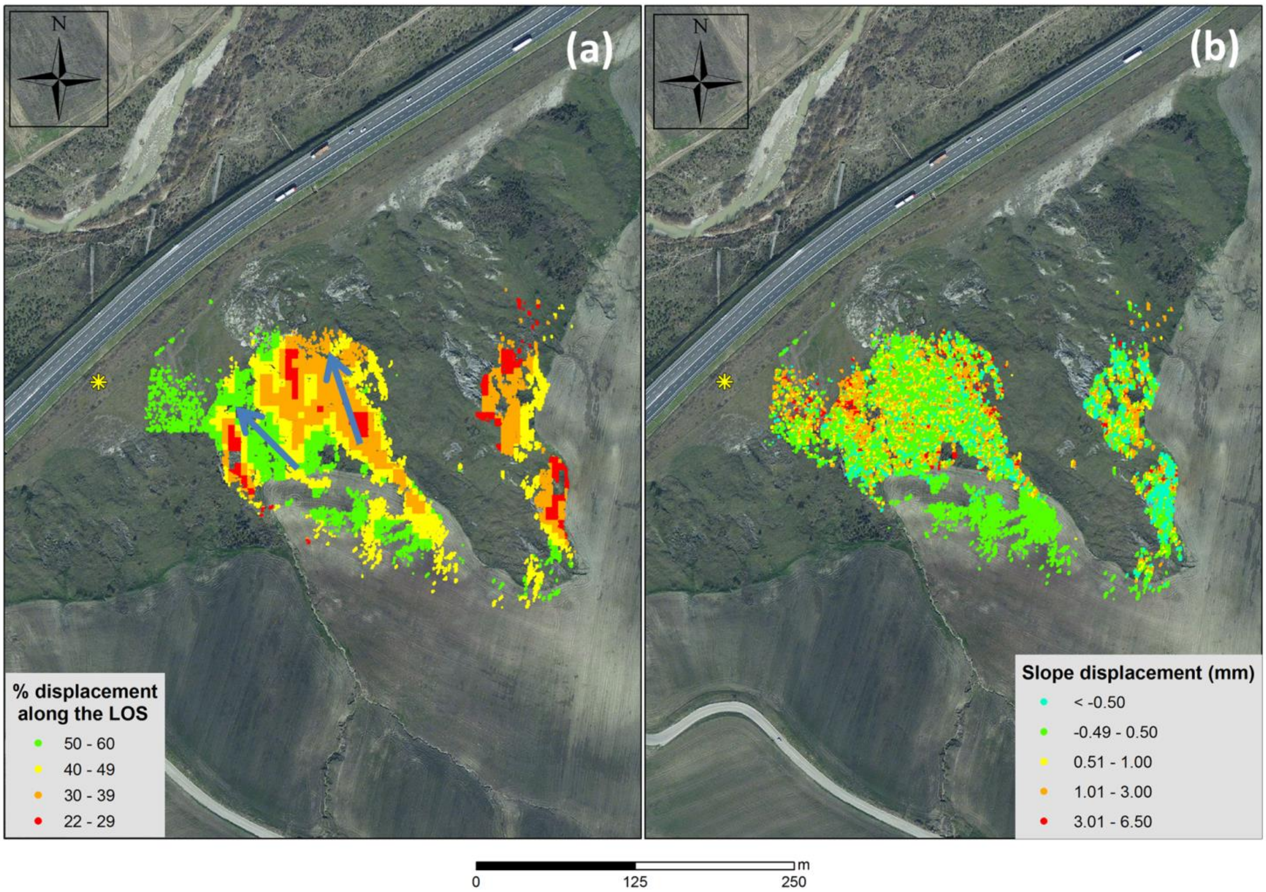

Figure 5. (a) *C* values map. Blue arrows indicate the downslope direction. (b) Cumulated displacement values projected along the downslope direction, referred to a period between 1 July 2014 and 1 November 2014. <u>The yellow asterisk in the left of the images represents the location of the GB-InSAR.</u>

Assuming that the studied landslide actually moves along the downslope direction, the GB-InSAR detectable real displacement percentage ranges between 22 and 60 % (Figure 5A).

In Figure 5B, an example of slope displacement map has been shown. Here, cumulated displacement data related to a period between 1 July and 1 November 2014 have been projected along the downslope direction. Data show as the area can be considered stable in the referred period; maximum displacement values of 4 mm in 4 months (eastern portion of observed scenario) can be still considered in the range of stability.

5.2.5 Time series extraction

In order to allow for a fast data transfer and velocity threshold comparison, some representative control points were selected, aimed at providing cumulated displacement time series. Control points were retrieved from the same displacement maps calculated as described in paragraph 5.2.2 and therefore can be relative to a time frame of 5 minutes, 8 hours or 24 hours.

In case of noisy data, instead of having a time series relative to a single pixel, these can be retrieved from a spatial average obtained from a small area consisting of few pixels.

5.2.6 Scenario cropping

Typically, the field of view of a GB-InSAR is larger than the actual area to be monitored. In fact, a portion of the radar image may be relative to the ground, sky, areas geometrically shadowed or covered by dense vegetation. These may be of no interest or even containing no information at all. For the case here studied around 50% of a radar image had a low coherence and was for all practical purposes, unusable. Therefore, a cropping of the ASCII displacement map occurred in order to frame only the relevant area.

5.3 Data transfer and visualization

The interferometric data generated by GB-InSAR, after the pre-processing and proper correction previously described, are ready for transfer to the DCPC. The transmission of these data to the DCPC is mediated by the middleware, which interrogates the GB-InSAR for tracking the state, detects the newest data, and reorders and marks them to properly build data time series to be transferred to DCPC.

Subsequently, the middleware manages communications with the DCPC, according to the implemented ad-hoc protocol. This ensures the security of data providers through encrypted authentication mechanisms, it allows for recovering missing or partially transmitted data, thus avoiding information loss, and provides data acquired by the sensors to the DCPC in a standardized format, JSON, able to guarantee uniformity between the various information provided by the various sensors types. All these particular features fully justify the adoption of an ad-hoc protocol for data transfer, instead of using a standard protocol such as FTP.

The data files produced by the GB-InSAR have already been locally pre-processed and result in a matrix expressed in ASCII code; the dimensions of the matrix are known and range from 1x1 (for the displacement of single control points) to 1001x1001 (for uncropped displacement maps). Before encapsulating these data in the message to be transferred to DCPC, the middleware converts them from ASCII code to character strings, using the standard coding ISO / IEC 8859-1, so being able to obtain a data compression with a factor equal to ≈8.

Eventually the DCPC is entrusted for cumulating the displacements relative to the control points, which are compared with the respective thresholds, and for visualizing the displacement maps as WebGIS layers, thus enabling data validation and the evaluation of the extension of moving surface.

6 Early warning procedures discussions

The GB-InSAR is part of a larger early warning system (LEWIS) which also includes other monitoring systems and simulation models. Therefore, to understand how GB-InSAR data can be used in an early warning perspective, it is necessary to make reference to LEWIS as a whole.

Any information, coming from the investigated sites and subsequently processed also by using the simulation models, is used to define an intervention model. This is based on the following elements: event scenarios, risk scenarios, levels of criticality, levels of alert.

Event scenarios describe the properties of expected phenomena in terms of dimension, velocity, involved material and occurrence probability. Occurrence probability depends on the associated time horizon, which should be equal to few hours at most, in the case of early warning systems.

Evaluation of occurrence probability is carried out by using information from monitoring systems and/or from outputs of adopted mathematical models for nowcasting. All the properties, to be analyzed for event scenarios, are listed below; a subdivision in classes is adopted for each one:

- landslide velocity (5 classes from slow to extremely rapid);
- landslide surface (5 classes from very small to very large);
- landslide scarp (5 classes from very small to very large);
- landslide volume (5 classes from extremely small to large);
- thickness (5 classes from very shallow to very deep);
- magnitude (3 classes: low, moderate, high), which combines the previous information;
- involved material (mud, debris, earth, rock, mixture of components);
- occurrence probability (zero, low, moderate, high, very high, equal to 1).

While some of the aforementioned parameters are determined by geological surveys, landslide velocity is directly derived from monitoring data (such as those collected by GB-InSAR). Landslide surface can be determined by geomorphological observation but is precisely quantified by GB-InSAR, thanks to its capability of producing 2D displacement maps.

Risk scenarios can be firstly grouped in the following three classes:

A. mud and/or debris movements which could induce a friction reduction between the vehicles and the tar and therefore facilitate slips;
B. road subsidence induced by landslides that could drag or drop vehicles;
C. falls of significant volumes and/or boulders that could crush or cover vehicles and constitute an obstacle for other~~s~~ vehicles.

For each previous risk scenario, six sub-scenarios can be identified ~~on the basis of~~based on the number of potentially involved infrastructures, carriageways and lanes (a. hydraulic infrastructures and/or barriers, b. only emergency lane, c. lane, d. fast lane, e. fast lane of the opposite carriageway, f. lane of the opposite carriageway). Thus, all possible risk scenarios are 18 (Figure 6)~~.~~, indicated with a couple of letters (Capital and small).

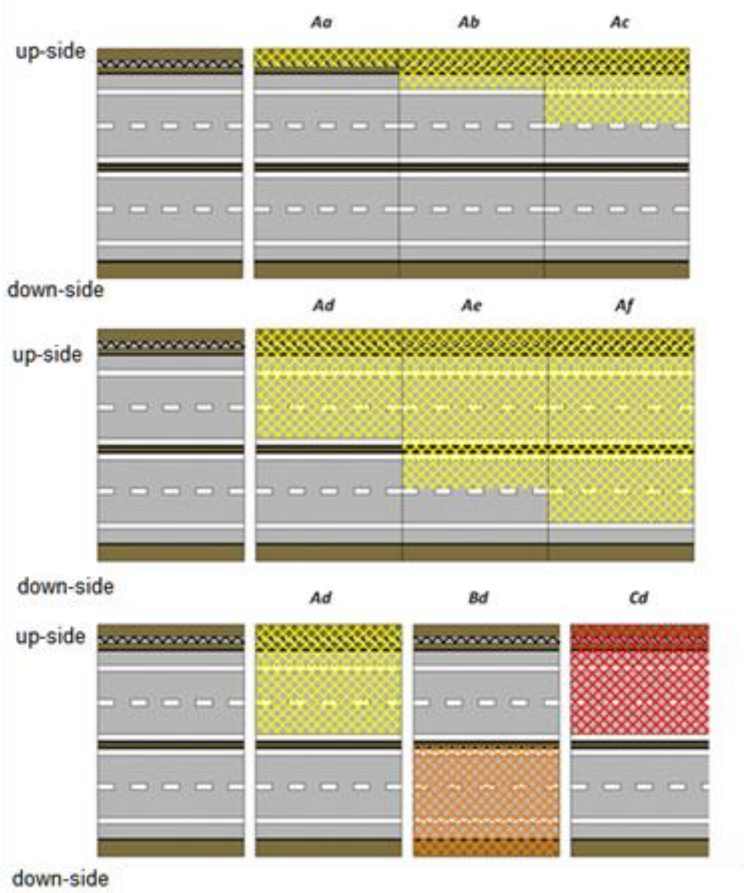

Figure 6. Top and middle: possible risk scenarios involving the scenario A (landslides that could reduce friction) to increasing sectors of the highway. Bottom: combinations of scenarios with ~~different~~ several types of phenomena (A, B, C) affect the emergency lane, lane and fast lane.

The following information is provided to DCPC:

- Measurements from sensors
- Model outputs

and four states are identified for each of them:

- state 0 = no variation
- state 1 = small variation
- state 2 = moderate variation
- state 3 = high variation.

In practice, for the GB-InSAR, such states are delimited by fixed velocity values (thresholds). In this application values have been selected according to the gathered data, the first threshold being just above the instrumental noise; the remaining have been set based on expert judgement waiting for a more robust calibration, which is possible only after at least a partial mobilization of the slope. Anyway, the system is open to any method for determining thresholds (Crosta and Agliardi, 2003; Du et al., 2013; Carlà et al., 2016a) and also to the use of other parameters (acceleration for example).

Besides information from sensors and models, other information is obtained from meteorological and hydrological models (named as indicators).

Indicators comprise weather forecasting and output of FLaIR and Sushi models (Sirangelo et al. 2003; Capparelli and Versace 2011) on the basis of observed and predicted (for the successive six hours) rainfall heights.
Two states are defined for indicators:

- state 0 = no variation or not significant,
- state 1 = significant variation.

To sum up, DCPC has the following information in any moment:

- state (0, 1) of indicators (IND),
- state (0, 1, 2, 3) of sensors and models running for the specific highway section (SEN),

and, on the basis of these states, four different decisions can be made by DCPC, one of which with three options.
All the possible decisions are illustrated in Table 1, in which the weight of the several sensors is assumed to be the same. Based on the notices of criticality levels provided by the DCPC, and on its own independent evaluations, the CCC issues the appropriate warning notices (Surveillance, Alert, Alarm and Warning) and makes decisions about the consequent actions.

State of sensors and/or models	**DCPC decisions**
All INDs and SENs are S0	0 - no decision
At least one IND is S1 and all SENs are S0	1 – SOD (Sensor On Demand) activation
At least one SEN is S1	2 – to intensify the presence up to 24 hours/day
At least *n* SENs are S1 or at least one SEN is S2	3/1 – to issue a notice of ordinary criticality (level 1)
At least *n* SENs are S2 or at least one SEN is S3	3/2 - to issue a notice of moderate criticality (level 2)
At least *n* SENs are S3	3/3 - to issue a notice of high or severe criticality (level 3)

Table 1. DCPC possible decisions.

The information of each sensor and the results produced by the models are used to assess, in each instant, the occurrence probability of an event scenario in the monitored areas and the possible risk scenarios.
This combination of heterogeneous data was carried out by identifying for each sensor and model a typical information (displacement, precipitation, inclination, etc.), evaluating the state in each instant, according to a threshold system, and combining this result for all sensors placed in a monitored geomorphological area.
The ~~final~~ result is constituted by the occurrence probability of an event scenario, that is associated with a specific action by the DCPC. In particular, if the occurrence probability is low, moderate or high it is necessary to issue a notice of criticality (ordinary - Level 1, moderate - Level 2, High - Level 3) to the CCC.
The DCPC sends two types of information:
1) criticality state of the single monitored geomorphological unit,
2) criticality state of the whole area.

The adopted communication protocol between the two centers for the exchange of information was carried out through a web service provided by the CCC, using the classes and attributes of the methodology named Datex II (which is a protocol for the exchange of traffic data). The use of the web service allowed to ensure the interoperability of data between the two centers, regardless of the used hardware and software architecture, through a persistent service capable of ensuring an immediate restoration of the connections, in case of malfunction and a continuous monitoring between the two centers, even in the absence of criticality.

7 Conclusions

The GB-InSAR is a monitoring tool that is becoming more and more used in landslide monitoring and early warning, especially thanks to its capability of producing real-time, 2D displacement maps. On the other hand, it still suffers from some drawbacks, such as the limitation of measuring only the LOS component of a target's movement and logistic issues like those owing to a massive production of data that may cause trouble for both storing capacity and data transfer. In particular, the latter is a more and more common problem of advanced technologies that are able to produce high quality data with a high acquisition frequency, which may leave the problem of find the balancing between exploiting all the information and at the same time avoiding unnecessary redundancy.

These problems have been addressed when a GB-InSAR was integrated within a complex early warning system (LEWIS) and only a limited internet connection was available. This situation required that a series of pre-elaboration processes and data management procedures took place in situ, in order to produce standardized and reduced files, carrying only the information needed when it was needed. The procedures mainly concerned the transmission of data averaged over determined time frames, proportionate with the kinematics of the monitored phenomenon. ~~Before~~Previously, transmission data were also corrected (both in terms of atmospheric noise and LOS) and reduced, by filtering out the information relative to the amplitude of the targets, by eliminating the areas not relevant for the monitoring and by transforming the matrices into strings.

As a result, GB-InSAR data converged into the early warning system and contributed to it by producing displacement time series of representative control points to be compared with fixed thresholds. Displacement maps were also available for data validation by expert operators and for retrieving information relative to the surface of the moving areas.

Competing interests. The authors declare that they have no conflict of interest.

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