

## Article

# Low-Cost GNSS Solution for Continuous Monitoring of Slope Instabilities Applied to Madonna del Sasso Sanctuary (NW Italy)

Davide Notti<sup>1\*</sup>, Alberto Cina<sup>2</sup>, Ambrogio Manzino<sup>2</sup>, Alessio Colombo<sup>3</sup>, Iosif Horea Bendea<sup>2</sup>, Paolo Mollo<sup>4</sup>, Daniele Giordan<sup>1</sup>

<sup>1</sup> Italian National Research Council, Research Institute for Geo-Hydrological Protection (CNR-IRPI), Strada delle Cacce 73, 10135 Torino, Italy; davide.notti@irpi.cnr.it; daniele.giordan@irpi.cnr.it;

<sup>2</sup> Politecnico di Torino – DIATI. +39 011 0907630, Corso Duca Degli Abruzzi, 24 10129 Torino, Italy; alberto.cina@polito.it; ambrogio.manzino@polito.it;

<sup>3</sup> Dipartimento Tematico Geologia e Dissesto, ARPA Piemonte - Agenzia Regionale per la Protezione Ambientale, Via Pio VII, 9, Torino, 10135, Italy alessio.colombo@arpa.piemonte.it

<sup>4</sup> CSP Innovazione nelle ICT s.c.a r.l., Strada del Lionetto 6, 10146, Torino, Italy; paolo.mollo@csp.it

\* Correspondence: davide.notti@irpi.cnr.it ;

**Abstract:** In the last years, the development of low-cost GNSS sensors allowed monitoring in a continuous way movement related to natural processes like landslides with increasing accuracy and limited efforts. In this work, we present the first results of an experimental low-cost GNSS continuous monitoring applied to the unstable slope affecting the Madonna del Sasso Sanctuary (NW Italy). The courtyard of Sanctuary is built of two unstable blocks delimited by high cliff. Previous studies and non-continuous monitoring showed that blocks suffer a seasonal cycle of thermal expansion and long-term trend to downslope of few millimeters per year. The presence of continuous monitoring solution, could be an essential help to better understand the kinematics of unstable slope and to recognize the beginning of a possible paroxysm phase that could end with a failure of the unstable area. We tested the accuracy of the instruments and the first year of experimental measurements are presented. We also propose a methodological approach that considers the use of automatized procedures for the identification of anomalous trends and a risk communication strategy based on monitoring data.

**Keywords:** Low-Cost GNSS; warning threshold; unstable slope; cultural heritage

## 1. Introduction

Landslides are one of the main natural hazards that can threaten the cultural heritage of humanity around the world [1,2]. The monitoring of unstable slope, joined with geological, geotechnical and geomorphological studies, is necessary to evaluate the risk and to plan mitigation strategy.

Around the world, several archaeological/cultural sites were the object of landslide monitoring, for instance: Macchu Picchu in Perú [3], the Monemvasia historical site in Greece [4], the Vardzia Byzantine monastery in Georgia [5]. In Italy, several cultural sites, potentially affected by a landslide, are monitored like: the town of Pitigliano [6], San Leo [7], Orvieto [8], or San Fratello [9].

The choice of the best monitoring solution depends on several factors, like landslides typology and velocity, the interaction with anthropic structures, and the available budget [10–12]. Another essential element is the purpose of the adopted solution since the structure of a monitoring system used for civil protection activity is different from a monitoring solution adopted for a periodical control of the slope evolution. For this reason, a general solution that can be selected in every site and

condition is usually challenging to define since the site-specific characteristics are an important element that should be considered during the definition of the monitoring network and strategy.

GNSS sensors are one of the well-known solutions for slope instabilities monitoring [13]. In the last years, the advance in GNSS technology allowed to create a new low-cost sensors generation that can provide continues monitoring with good precision and accuracy and limited costs [14,15]. Nowadays, the use of low-cost solutions is commonly considered not robust enough to support early-warning procedures, but its deployment can be considered for permanent installations aimed to control the evolution of slope instability and to detect critical trends. In this context, these low-cost solutions can be regarded as a good alternative to periodical measurement campaigns that can be supported with and to focus more precise and high-cost monitoring solutions only and when it is necessary. As described in [16], the acquisition of monitoring data is the first essential step for the set-up of a decision-makers support procedure based on monitoring data. Other important elements are a correct interpretation of monitoring data and a good communication strategy that can be used to share monitoring results with decision-makers and people that can be involved in the evolution of the slope instability. Correct risk communication is nowadays considered an essential element for a proper management of emergencies [17].

In this study, we present the first outcome of a continue and near-real-time monitoring network based on low-cost GNSS of the unstable cliff that affects the part of the adjacent area of the Madonna del Sasso Sanctuary, an important cultural/religious heritage, facing the Orta lake in Piemonte region (NW Italy). The slope instability that affected the frontal part of the Sanctuary courtyard has been studied from different authors in the last years [18–22], and it is monitored by ARPA Piemonte (the regional environmental protection agency of Piemonte). In this work, the main feature of installed low-cost GNSS systems and the first outcome of first-year monitoring are presented and discussed. We also propose a possible monitoring strategy that considers the use of automatized procedures for the identification of anomalous trends and a risk communication procedure based on the use of bulletins [16] and Operative Monographies [23].

## 2. Study area and past monitoring analysis.

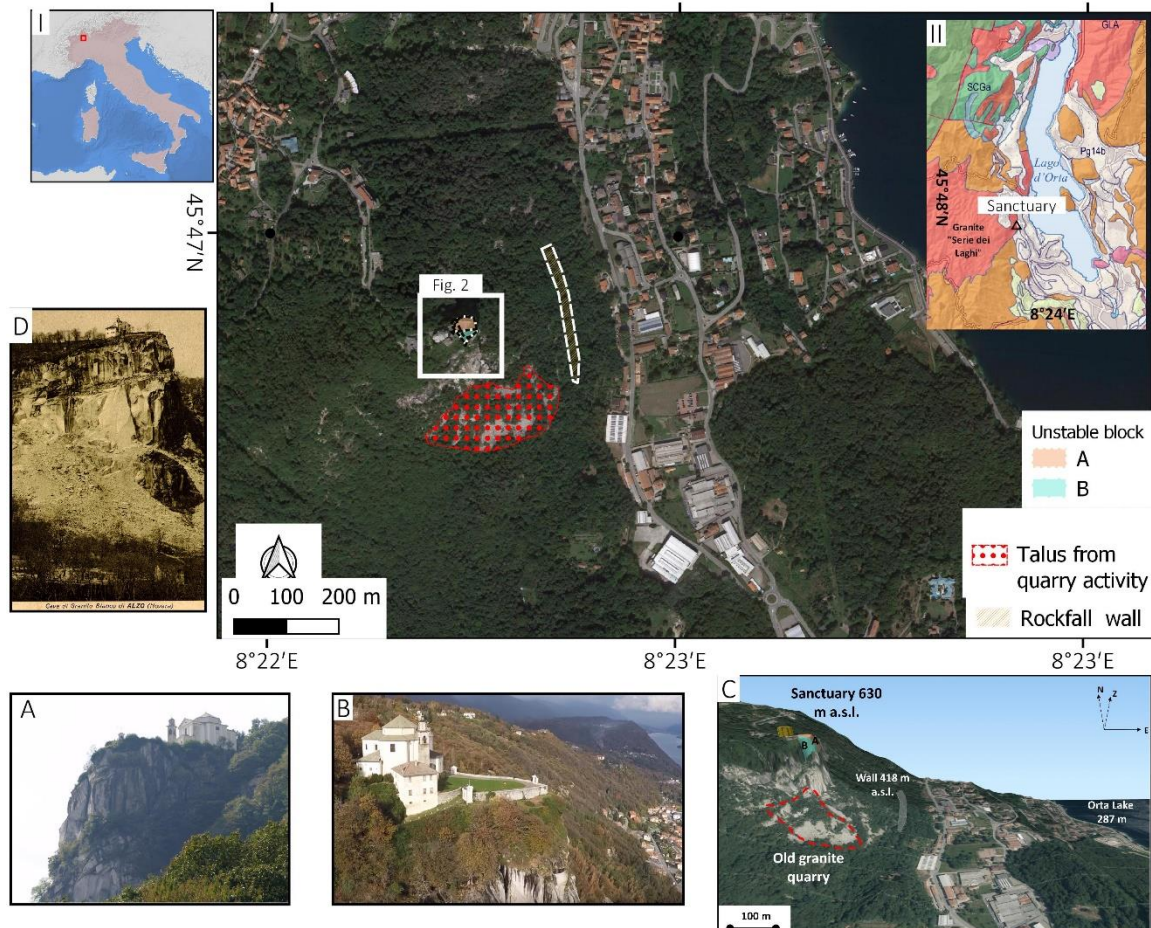
### 2.1 Geological framework

The study area is located in NW Italy, on the western shore of the Orta Lake. The Madonna del Sasso sanctuary is located on the top of a cliff at 650 m a.s.l. delimited by vertical slopes on three sides (N, E, and S) (**Figure 1** A and B). The scarps have a height of about 200 m. The sanctuary, built in XVIII-century, is an important cultural heritage visited by many tourists and peregrines. The cliff is characterized by the presence of different discontinuity sets that can create critical intersections, which are a predisposing factor for the activation of rockslides. The presence of this instability is quite evident in the frontal part of the courtyard, where one of the main discontinuity crosses from SE to NW the entire court. The instability of the courtyard in front of the sanctuary is a factor of risk for people that visit this important cultural heritage site, but also for people that live at the base of the cliff, close to the Orta Lake.

From a geological point of view, the sanctuary is located on a massive granite outcrop known as Granito di Alzo [24]. This unit belongs to the non-metamorphosed, and generally low deformed, granitic masses, related to a late-Hercynian magmatic intrusion (lower Permian), which outcrops along the contact between the lithologies of the “Serie dei Laghi” and the Ivrea-Verbano Zone. These granites, commonly known as “Graniti dei Laghi,” make a large batholith elongated in NE–SW direction (**Figure 1** II). The most widespread facies of the Alzo-Roccapietra pluton is a white, medium-grained biotitic granite. The pluton was not significantly tilted after the first intrusion and preserved its original position. The granite bedrock in which sanctuary was built shows excellent geomechanical features ( $GSI > 70$  and high uniaxial compression strength  $> 50$  MPa), While the fractured blocks present poor quality [20]

The actual aspect of this cliff is also related to a combination of the structural settings and the presence of a quarry along the southern side of the slope that stopped its activity a few decades ago (**Figure 1 D**).

At the base of the cliff, talus and boulders are the result of past quarry activity and rockfalls. According to the critical stability condition and the presence of several elements at risk, at the end of the twentieth century was erected a protection wall aimed to reduce the possibility that detached blocks can reach the provincial roads and the nearby buildings.



**Figure 1.** I) location and II ) geological settings of Madonna del Sasso site from the geological map of Piemonte [25]. In the main aerial image are visible: i) the location Sanctuary and the courtyard ii) the ancient quarry deposits, ii) a rockfall wall designed to protect the elements at risk. The photos 1A and 1B represent the view of Sanctuary and unstable slope from North and South, respectively. The image 1C shows a 3D view from the south of the unstable cliff. The images 1D shows a historical view of the southern cliff of Sanctuary with the active quarry in 1931 (photo credit <https://www.accendiamolamemoria.it/gallerymadonnasasso>).

## 2.2 Structural and geomechanical characterization

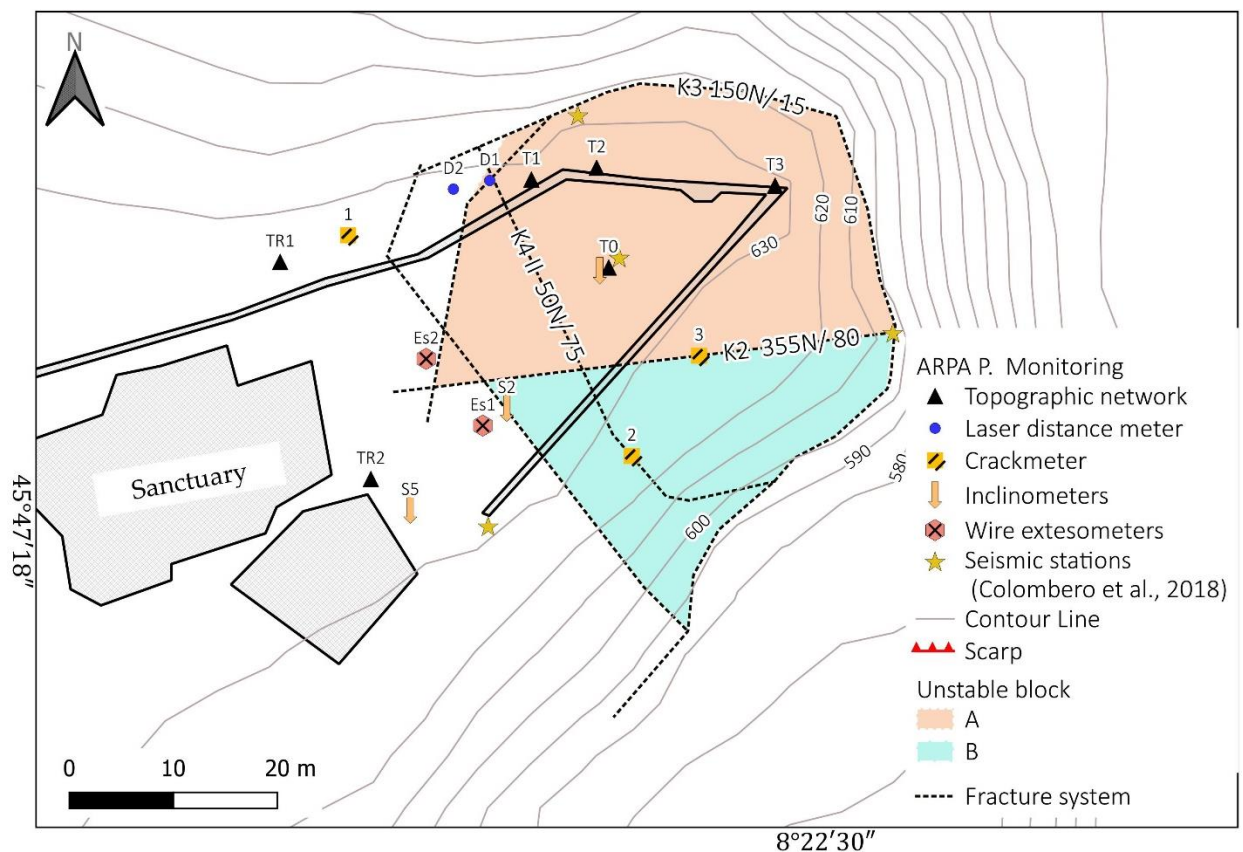
Several studies were made on Madonna del Sasso site from the early '90s when some evidence of instability appeared and the first countermeasures, like the rockfalls wall, were realized.

[18] made a geomechanical characterization of the site. The detailed investigation carried out also using geophysical methods by Colombero et al. [20,21,26] allowed a good improvement of the knowledge of this case. In particular, [21] identified an open and pervasive fractures system delimiting two prone-to-fall sectors (A and B) having estimated volumes of 6.000 and 6.300 m<sup>3</sup>, respectively. The two sectors are separated by the sub-



vertical fracture (**Figure 2**) K2 (355/80) having an approximate open depth of 15 m, and are truncated at the base by the low-dipping fracture K3 (153/15). Fractures K1 (113/65) and k4 (52/80) separate the back of the two compartments from the stable cliff. In particular, fracture K4 shows an evident displacement step on the panoramic square located at the top of the cliff. The investigation found that the fracture is open up to a depth of about 16 m [21].

The studies of Colombero also allowed the identification of the presence and persistence of deep and pervasive fractures systems within the rock mass, which isolate the prone-to-fall frontal portions of the cliff. Moreover, the quite low seismic velocities in the whole unstable sector that probably suggest the widespread presence of dry cracks and minor fractures at different scales.



**Figure 2.** A detail of the fracture systems that limit the unstable blocks “A” and “B” on the base of the work of [18,21] and former and current monitoring system installed by ARPA and Regione Piemonte on Madonna del Sasso site and location of the seismic stations used by [26]

### 2.3 Unstable slope behavior

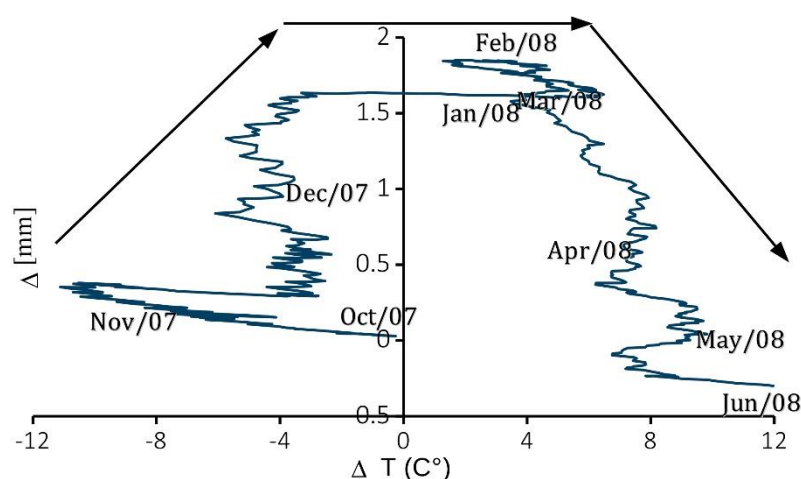
The monitoring system installed by Regione Piemonte and ARPA since 1990 has been composed of several instruments like inclinometers, laser distance meters, topographic measurements [19]. Most of these monitoring activities have been performed by limited periods. Wire-strain gauges collected data only for a short period and were used to understand the thermal behavior of rock mass and fractures systems (**Figure 2**). In [22], the geo-structural study was combined with borehole seismic and micro-seismic monitoring campaigns, and a detailed analysis of topographic monitoring

data of ARPA Piemonte was used to understand the rock mass evolution and fracture system behavior. The most important results of Colombero studies are:

1. A seasonal cycle of thermal expansion of the rock mass. This interesting behavior was detected by combining micro-seismic (MS) investigation, topographic monitoring, and wire-strain gauge measure. The MS rate was coherently recognized to be mainly driven by temperature. The maximum frequency of events occurred during summer, with thermal expansion. While a minimum of MS event was recorded in winter months when the fractures are opening due to the reduction of dilatation effect on the bedrock.
2. The micro-seismic investigation pointed out the presence of micro-seismic events, which are related to rapid air temperature variations (temporal gradient) or marked temperature differences between the cliff's faces (spatial gradient). These events could cause differential thermal dilation and induce thermal stresses leading to microcracking processes within the cliff, as already demonstrated by [27]
3. The temperature control was found to be the cause not only of fracture opening/closing with a seasonal frequency but also for a general change in the vibration directions measured during micro-seismic investigations of the two unstable blocks. Also, the daily cycle of thermal variation influences as observed on seismic noise resonance [22].
4. A long term trend in which block A tends to slide towards NE of few millimeters per year. This trend is probably related to progressive weakness and degradation of rock bridges in fractures caused by the expansion-contraction cycle.

Also, past displacement monitoring campaigns (2007–2008) at the wire extensometers across fracture K4 in highlighted a partially reversible seasonal fluctuation of fracture opening, driven by air temperature fluctuations. This trend is visible in **Figure 3**, where the change of air temperature is compared with the changes in fracture opening from October 2007 to June 2008. Maximum fracture opening was recorded during winter months, likely due to the rock mass thermal contraction, while the minimum opening was found in summer as a result of the rock mass thermal expansion.

[26] also suggested to install a continuous topographic monitoring system, joined with micro-seismic noise measure on the site, in order to better define the seasonal cycle of thermal dilation and the long term cycle of degradation and slide of the blocks. According to this suggestion, this site has been chosen for the development of the presented low-cost GNSS monitoring network.



**Figure 3.** Correlation between temperature variation (X-axis) and the opening of the fracture (Y-axis) variation calculate on a monthly interval, for the period October 2007 – June 2008. Data source: wire extensometers of ARPA Piemonte.

### 3. Materials and Methods

The work made on Madonna del Sasso site was divided on four main packages:

5. The production of an operative monography. In this project, we decided to adopt the operative monography approach [23] for the acquisition and organization of all available information (e.g., monitoring data, thematic studies, publications, and maps). The first step of the project has been the collection, analysis, and organization of the available material. This approach is particularly useful when the analyzed site has a long history of studies, in situ exploration, and monitoring that could have produced a large amount of data not always well organized. The operative monography has been very useful for the definition of what has been already defined by the previous study and use this information for the identification of better positions for GNSS installation.
6. The re-analysis of ARPA-Piemonte topographic network data. The topographic dataset acquired by ARPA Piemonte is available from 2006, and it represents the most important source of information for the definition of displacement trends. We re-analyze this data in order to have a long-term trend to compare with the new GNSS data.
7. Design, implementation and test of GNSS low-cost sensors. The GNSS system has been developed and tested in the laboratory. After these first phases, the system has been installed in the unstable area and it becomes the first in place continuous topographic monitoring solution adopted for the study of the evolution of the Madonna del Sasso cliff. Two low-cost GNSS sensors were installed on-site to measure the position of two different representative points continuously. The adopted monitoring network is equipped with hardware and software solutions that guarantee not only the in situ acquisition, but also the raw data transmission and processing.
8. Definition of a semi-automatic early warning (EW) procedure. The final step of the project has been the development of a GNSS results analysis aimed to implement an early warning (EW) procedure. The EW procedure considers the definition of displacement thresholds on the short and long term that can be used for fast identification of critical trends that can be indicative of a possible increase of blocks instability.

#### 3.1 The Operative monography

As mentioned before, the Madonna del Sasso case study has been studied by several research groups, and now is one of the monitored slope instability in the Piemonte Region. The presence of many studies, projects, risk assessment analyses and remedial works means the presence of a large amount of data and information often distributed in different local or regional administrations or research centers. The regional Environmental Protection Agency (ARPA Piemonte) collected part of the information in a system called SIFRAP (Sistema informativo fenomeni franosi in Piemonte – information System of Piemonte region landslides). SIFRAP system is composed of cartographic information (organized using a web GIS platform) and different forms with a progressive level of detail. In particular, SIFRAP forms is organized in three different levels of detail: i) level one – a synthetic description of the landslide according to with the IFFI Project, the Italian landslide inventory [28]; ii) level two – composed by level one and a more detailed description of available information and a dedicated geomorphological map of the slope instability; iii) the highest level that is available only for few landslides in Piemonte and that provides a detailed study of the slope instability. For Madonna del Sasso, the SIFRAP system has a second level form available (<http://webgis.arpa.piemonte.it/Web22/sifrap/iiLivelli/103-01641-00.pdf>)

As presented and discussed in [23], one of the most critical elements that often characterized slope instabilities monitored or studied for a long time is the availability of many data without a good organization and representation of obtained results. Very often, data have been acquired by different working groups and preserved by different private companies or administrations. A practical (and

also standardized) organization of what we already know about the studied phenomenon is the first fundamental step for a better management of a possible emergency related to an improvement of the activity of the slope instability, but also for the identification of possible weak points in the state of the art of available studies. The SIFRAP database (in Italian) gives a good representation of the case study, but a large amount of information acquired in the last three decades is not adequately represented.

The OM facilitates the assessment of the state of knowledge, which is a necessary step for a complete comprehension of each phenomenon. The document is focused on end-users like civil protection, other researcher and technician, and local authorities. In the case of Madonna del Sasso, we collected the information coming from Lancellotta and Colombero studies. The chapter of monitoring resumes the main result of ARPA and Regione Piemonte monitoring, and the interpretation of micro-seismic monitoring results made by Colombero. The outcomes of the new GNSS monitoring are added in “further studies in progress” chapter that can be progressively updated on the base of new monitoring and study results.

The use of OM has been very useful for the collection and organization of available material that has been the base for the GNSS monitoring system development and installation. Part of OM results are synthesized in the description of the Madonna del Sasso case study and the chapter dedicated to the topographic monitoring result analysis.

### 3.2 Available topographic monitoring: data analysis

The most important dataset comes from topographic measurements (active from 2006) and laser distance meters (active from 2009) installed and measured by ARPA Piemonte. All monitoring instruments are installed only on the block A. ARPA installed on this site four topographic benchmarks: three are located on the parapet of the courtyard (T1, T2, and T3), and one in the unstable sector of the courtyard (T0). Two adjunctive benchmarks are located in a stable area near the sanctuary and they are used as reference points. The benchmarks are measured about 2–3 times per year since 2006. The two laser distance meters are located across the K4 fracture on the north side of the courtyard, and the laser distance meters provide about two-measure per year since 2009 (**Figure 2**).

Available Satellite InSAR data (2003–2009) are not very significant on this site as only one PS of Radarsat satellite is available. However, the SAR was taken into consideration because its trend is comparable with the topographic measurements and a PS located nearby in a stable area is used as a local benchmark. The availability of a topographic network is an essential source of information that is fundamental for a long-period characterization of the slope instability. Available topographic data Table 1 have been re-processed to choose the place where install the new GNSS, and at the same time, they will be used for validation of GNSS data for the first year of measurement (2018–2019).

**Table 1.** List of ARPA Piemonte monitoring data re-analyzed for this work

CODE	Name	Type	from	to	Active
L7MDSA0	D1	Laser distance meters	2009	2018	y
L7MDSA1	D2	Laser distance meters	2009	2018	y
T7MDSA3	T0	Topographic Benchmark	2006	2019	y
T7MDSA2	T1	Topographic Benchmark	2006	2019	y
T7MDSA1	T2	Topographic Benchmark	2006	2019	y
T7MDSA0	T3	Topographic Benchmark	2006	2019	y
AO7ND	PS1	InSAR data (RADARSAT)	2003	2009	n

### 3.3 Desing, implementation and installation of a low-cost GNSS monitoring system

The previous research [15] showed that, even with mass-market receivers, it was possible to detect displacements imposed up to five millimeters in planimetry and one centimeter in altimetry. In this experience, the best results were achieved with an uBlox EVK7T receiver, a Garmin GA38 mass-market antenna and when the distance from the master station was about few hundred meters. The phase ambiguities fixing was performed with the use of the L1 GPS frequency only.

The instrumentation installed on the Madonna del Sasso sites involved the use of mass-market uBlox EVK8T receivers that provide data on the first frequency of the three GNSS constellations: GPS, Galileo and Beidou, again a Garmin GA38 antenna (Figure 4) able to trace these frequencies and a distance from the nearest permanent station of less than 10 km.

A short distance between master and rover makes it possible to neglect the tropospheric and ionospheric residues in the double phase differences, and it has almost always been possible to integer fix whole-phase ambiguities with multiple constellations and one frequency.

However, during the months in which the receivers provided their data, the Beidou constellation did not yet have a sufficient number of satellites to improve the robustness of the positioning. The Galileo constellation, which is more visible in Europe, although not yet complete, has for now only provided help in fixing the GPS phase ambiguities since the software was not yet able to reach the Galileo ambiguity. Despite this, we have chosen to use these three constellations because of the future and rapid improvements in both the constellations and the processing software used.

As shown in figure 4, the mass market antennas have been mounted on a specially constructed aluminum plate that forms the circular ground plane. A second plate was attached to this plate with a spacer and finally a pin with a 5/8 thread that allows the antenna to be mounted on any type of topographic base. Under the first radome a triaxial accelerometer and a temperature sensor have been installed, which, together with the antenna cable, are connected to the operational control unit visible in the right part of . The prototypal multisensor box with

Before installing the antennas, precision measurements were carried out to calculate the position of the phase center with respect to the BAM (bottom of antenna mount) but also with respect to the top of the small dome of each antenna. For deformation monitoring, this operation is not mandatory as only relative movements are required.

It was useful both because the “zero” position was calculated with high precision with geodetic antennas and receivers, and because the dome was painted in a checkerboard pattern to be observed photogrammetrically.

The coordinates of the center of the dome have been used and will, therefore, be used as a control point in these reliefs (the GSD is about 6mm). The position of the phase center was obtained with an accuracy of one mm utilizing simultaneous measurements with a geodetic receiver and calibrated antenna, using the “antenna swapping” technique. The planimetric phase center coincides with such precision with the physical center of the antenna.

A triaxial accelerometer “4030” from TE Connectivity®, usually used for structural monitoring, was mounted on the bottom of the ground plane under the GNSS antenna. This sensor, with a range of  $\pm 2$  g, provides an mV output, which can be converted into acceleration values and relative angular values. In particular, a rotation of  $1^\circ$  corresponds to a voltage equal to 11.11 mV and the residual noise is 0.24 mV at an angular value of  $0.022^\circ$  (0.38 mrad or 3.8 mm@10 m). The monitoring of angular values with acceleration measurements is theoretically independent of time, not being linked to integration operations as in the case of gyroscopes, and this makes the accelerometric angular measurement independent of the acquisition measurement duration. The voltage output required an interface with a special card and management software that outputs the “raw” acceleration values on the three axes and the time indication. The accelerometers were mounted on the lower part of the antenna ground using a compass to orient them and after having made this plane perfectly horizontal. Each sensor, before being installed, has been individually calibrated. The calibration matrix E (1) is applied in real-time to the measurements.



The raw values are usually influenced on each axis by a translational bias, a scale factor and an error due to the non-orthogonality of the three axes. These biases were estimated in the laboratory with the “six faces” calibration procedure [4,29]

$$\begin{pmatrix} l_x \\ l_y \\ l_z \end{pmatrix} = \begin{bmatrix} e_1^1 & e_1^2 & e_1^3 & e_1^4 \\ e_2^1 & e_2^2 & e_2^3 & e_2^4 \\ e_3^1 & e_3^2 & e_3^3 & e_3^4 \end{bmatrix} \begin{pmatrix} t_1 \\ t_2 \\ t_3 \\ 1 \end{pmatrix} \quad (1)$$

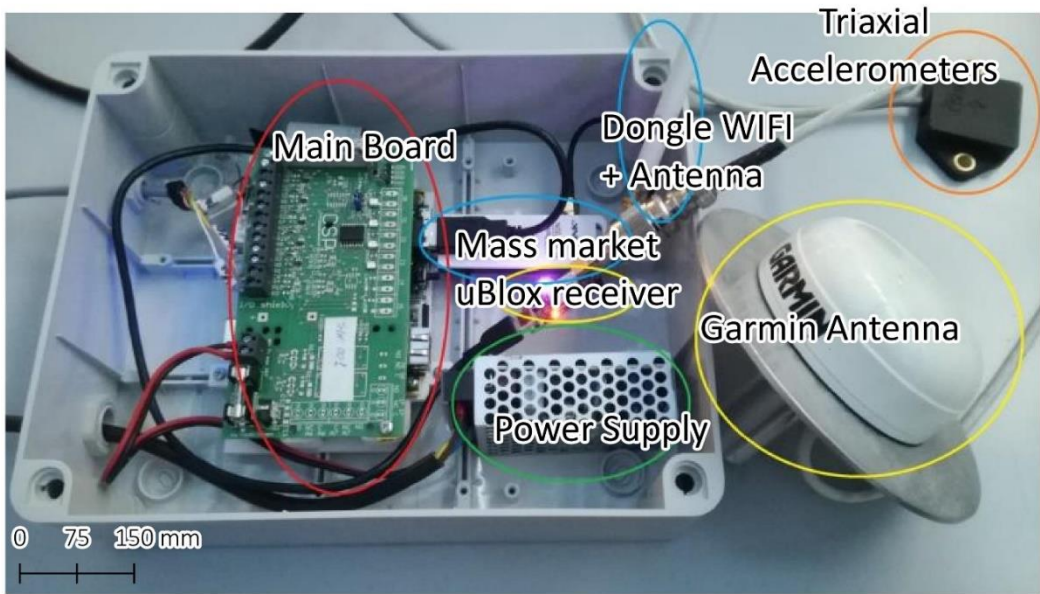
where the  $l$  values are the readings on the three axes while the  $t$  values represent the theoretical values that these readings should have.

After calibration, the accuracy detected by the laboratory is 0.02 °, better than an order of magnitude than that which would occur without calibration. After the examination of six “4030” accelerometers calibration constant, it was found that the calibration values differ from each other considerably: it is therefore not possible to perform an average calibration for this family of sensors that must be individually calibrated.

Near the accelerometer, below the ground, a temperature probe has been inserted, which is transmitted together with the accelerometric data to the control center. During the measurements performed in the laboratory, there was no particular relationship between the accelerometric and temperature measurements.

### 3.3.1 Hardware technology installed

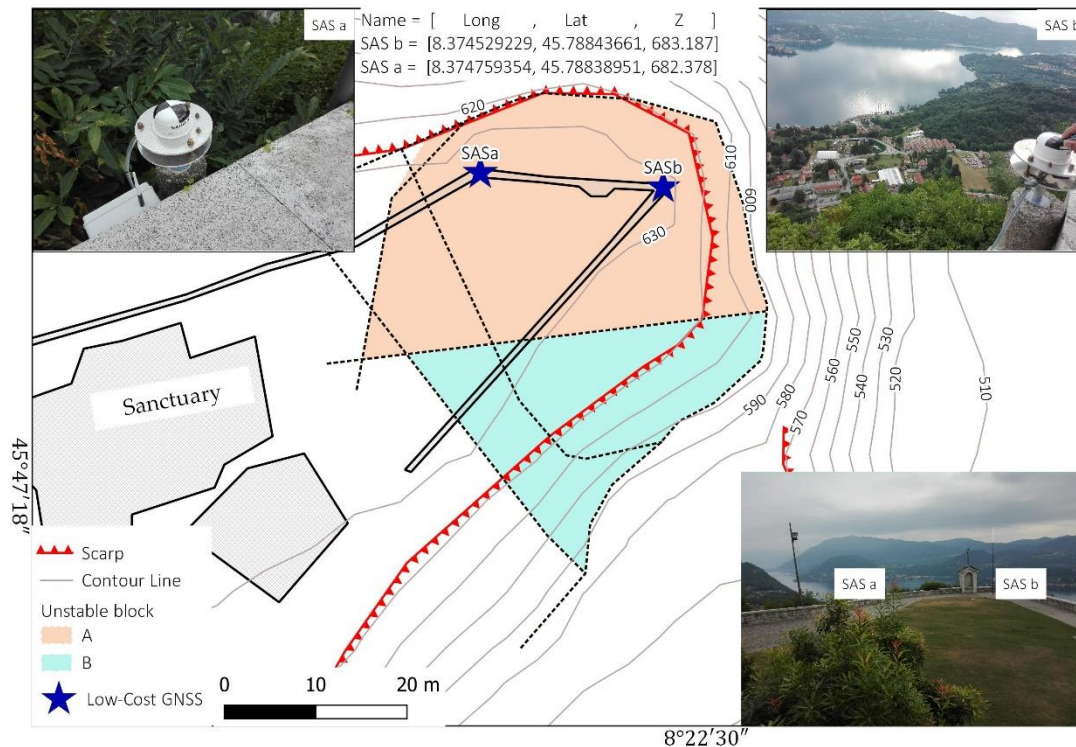
The set of instruments installed on the monitoring sites can be seen in figure 4, where can be seen in the image of the prototype used for the tuning of all installed instruments. The mainboard that controls all the sensors is a micro pc with a Linux operating system. It is equipped with four powered USB interfaces, a removable memory card on which the operating system and data are stored. The micro PC is programmable by remote control like any Linux computer. It manages the dialogue with the uBlox receiver, with the accelerometer and the temperature sensor. The system must be externally powered either by a power supply or by a solar panel. The micro PC also manages the transmission of data to the control center, both the accelerometric and temperature data and the corrections in the RTCM format of the GNSS sensor. The cost of installed instrumentation is about 500 € (**Table 2**). The installation cost is very dependent on the characteristics of the site, its accessibility and the existing infrastructures (electricity grid, data transmission network). Under normal conditions, the cost is empirically estimated about € 500. In figure 5 is shown the ubication of the instruments in the courtyard of the Sanctuary.



**Figure 4.** The prototypal multisensor box with

**Table 2.** Low-Cost instrumentation installed on Madonna del Sasso site

Instrument	Unit Cost
GNSS uBlox L1	70 €
Garmin antenna	50 €
Tri-axial accelerometer + temperature sensor	150 €
Micro PC mainboard, plastic box and dongle Wi-Fi	200 €
batch procedure RTKlib per RT e PP from NRTK SPIN	free



**Figure 5.** The ubication of GNSS antennas SASa and SASb

### 3.3.2 GNSS data processing.

The processing of data from low-cost sensors took place using open source software from the "RTKLIB" library (<http://www.rtklib.com>). This software is installed both inside the minicomputer that transmits the RTCM stream of the uBlox receiver, and at the control center.

In the control center, the STR2STR program stores the RTCM flow received every second from the monitoring stations, in a data file packaged both hourly and daily. Even the automatic GNSS data processing techniques mainly refer to a series of RTKLIB free-use package programs as well as to some software, specifically built and necessary for these purposes, aimed at scheduling a different operation:

9. Automatic data acquisition from Ublox single-frequency receivers;
10. Daily packaging of these data according to standard RINEX formats;
11. Data acquisition of real or virtual master stations for post-processing;
12. Automatic post-processing of the rover stations with master stations or with virtual stations for movement monitoring;
13. Post-processing of the data of stations close to each other, for deformation monitoring;
14. Automatic sending of a reasoned report of the post-processing results both via email and to web platform;
15. Construction of graphs of displacements and deformations and sending it specialized technicians to interpret the results.

As mentioned before, the choice was to trace, in addition to the GPS constellation, also the Galileo and Beidou constellations rather than the Glonass constellation. The choice is due to the future improvement, due both to the completion of the two constellations and to the more precise future codes.

Another topic is the real-time transmission of data. Even if post-processing involves daily processing data, for which acquisition rates of 30 seconds are sufficient, data transmission in the

RTCM 3.01 format at a rate of 1s does not require special equipment. This can allow for post-processing as well as future real-time control. These files in RTCM format every hour and every day are converted into a RINEX format measurement file through the "CONVBIN" command. Finally, it is necessary to treat this data with the same periodicity, this is possible through the "RNx2RTKP" command. However, differential post-processing, requires the use of data from at least one master station. For the stations of Madonna del Sasso, the master station is the permanent station of Gozzano, about 9 km away.

At the end of the conversion, and the differential processing in post-processing, the RINEX observation and navigation files must be compressed and archived, while the RTCM3 format files that generated them must be deleted.

The output of the differential treatment is a file that is complex enough to read and, in any case, it is necessary to automate the required information to the user after having accurately interpreted the result, in particular, its accuracy, the fixing or not of the phase ambiguities and the significance of possible displacements.

The results of the differential positioning come together in ASCII files of different names and extensions: ".POS".

Finally, for each of these results files, the last line representing the calculation summary is extracted and appended to an extension file: ".SUM", which contains a summary of the results of all daily treatments for all stations and for any treatment. Processing is considered to be failed if the complete fixing of the phase ambiguities is not achieved with a safety coefficient (ratio test) greater than or equal to four.

Finally, a report is sent by e-mail of the daily post-processing outputs; these outputs and the statistical controls are also deposited in the cloud, together with the graphic drawings and the hourly processing reports.

Alert information is provided through a table containing codes similar to traffic light signals, which will be described later.

All these commands are scheduled on the computer and are completely automatic.

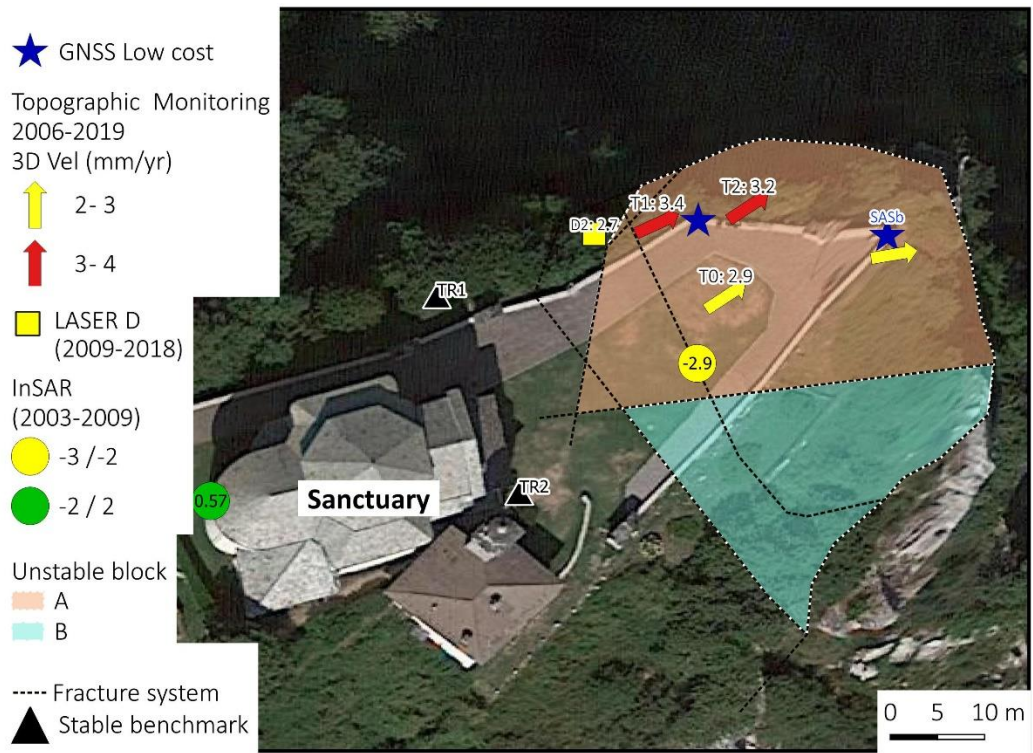
## 4. Results

### 4.1 Monitoring data processing

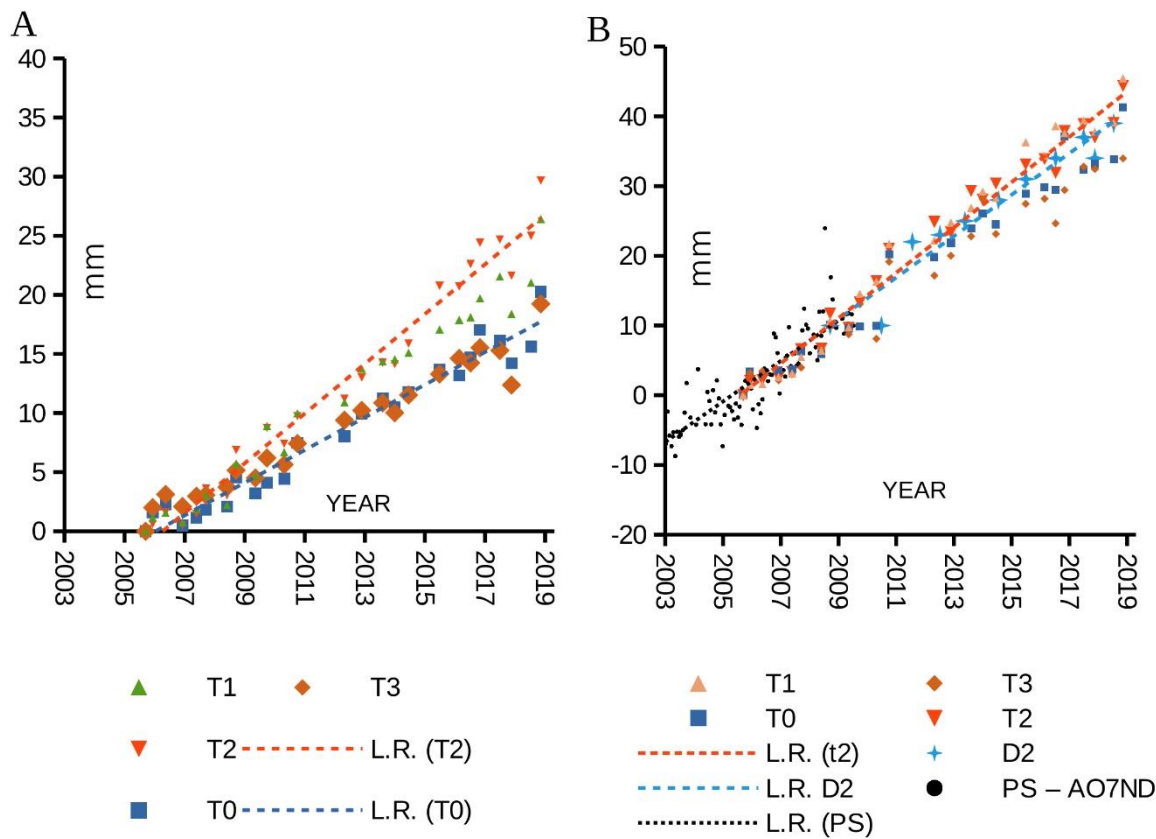
As mentioned in chapter 3.2, available monitoring data comes from on-site topographic monitoring network and satellite InSAR data. The data from the InSAR satellite (Radarsat) cover the period 2003-2009, and the number of available points in the studied area is limited. This data are essential to confirm that points used as reference elements for topographic measurements are stable and that there is a good correlation between satellite data and topographic measurements.

The in situ monitoring instruments active on the sites are four topographic benchmarks and two laser distance meters that made discontinues measures (up to 3 / 4 measure per year) **Figure 6**. All the monitoring system are in agreement to show the long-term trend of block A to slide toward NE with a rate of  $1 \div 2$  mm/yr, including the vertical displacement (downward) the entire displacement range about  $2.6 \div 3.6$  (Table 3). The times series of topographic data show seasonal oscillations that are in agreement with the documented seasonal cycle ( **Figure 7**). By de-trending horizontal displacement, it is possible to observe  $\pm 2$  mm of displacement oscillation.





**Figure 6.** Topographic displacement from ARPA Piemonte instruments and location of the new low-cost GNSS systems



**Figure 7.** A) Time Series of 2-D displacement of the topographic benchmarks (T0, T1, T2, T3); B) 3-D Time-series displacement and also compared with InSAR data (PS AO7ND, Radarsat ascending) of ARPA Piemonte and laser distance meters D2

**Table 3.** Displacement rate, azimuth, and dip measured by topographic benchmark, InSAR and laser distance meter monitoring of ARPA Piemonte

Instrument	Topographic benchmarks				Laser distance	InSAR
Name	T0	T3	T2	T1	D2	Radarsat PS <sub>VLOS</sub>
Temporal span	2006-2019				2009-2018	2003-2009
Vel <sub>xy</sub> mm/yr	1.4	1.2	2.1	1.7	-	
Azimuth (°)	55	73	55	64	-	80 <sub>LOS</sub>
Vel <sub>xyz</sub> mm/yr	2.9	2.6	3.2	3.4	2.7 <sub>(lin)</sub>	2.9 <sub>LOS</sub>
Dip(°)	61	63	50	58	-	56 <sub>LOS</sub>

#### 4.2. GNSS data processing: quality and reliability

An example of a daily tabular report concerning the computing of baseline vectors of the SASa station is shown in **Table 4**. The master station is, in this case, Gozzano.

**Table 4.** The columns show: the day and time of measurement; latitude, longitude in decimal degree; height the elevation in m a.s.l.; *Q*: the quality coefficient (1=ambiguity fix); *ns*: the number of satellites used; *sdn-sdun*: the variance covariance matrix; *age*: the average calculation delay of the data in seconds; *ratio*: the value of the “ratio test”.

date	time	latitude	longitude	height(m)	Q	ns	sdn(m)	sde(m)	sdu(m)	sdne(m)	sdeu(m)	sdun(m)	age(s)	ratio
2018/08/02	13:15:55	45.788436549	8.374529235	683.1674	1	11	0.0001	0.0000	0.0001	0.0000	0.000	-0.0000	1.99	350.7
2018/08/03	00:04:29	45.788436857	8.374528988	683.2268	1	14	0.0001	0.0000	0.0001	-0.0000	0.000	0.0000	4.99	5.0
2018/08/04	00:04:31	45.788436569	8.374529229	683.1778	1	10	0.0000	0.0000	0.0001	0.0000	0.000	0.0000	2.99	220.0
2018/08/05	00:04:30	45.788436607	8.374529364	683.2022	1	15	0.0003	0.0003	0.0006	-0.0000	0.000	0.0002	-1.00	4.0
2018/08/06	00:04:22	45.788436552	8.374529250	683.1782	1	15	0.0000	0.0000	0.0001	0.0000	-0.000	-0.0000	3.98	272.6
2018/08/07	00:04:23	45.788436586	8.374529276	683.1765	1	10	0.0000	0.0000	0.0001	0.0000	0.000	0.0000	2.00	332.6

The calculations of displacements and deformations between the two neighboring stations of Madonna del Sasso are then read by a software that analyzes the significance of the results and constructs suitable graphs for this purpose. In particular, for these series and each of the three components, two types of control are performed:

- check of a possible short-term fast movement;
- check of a potential anomalous trend over a long-term period.

##### 4.2.1 Alert assessment with shorth term displacement.

Based on the historical series of each site and each component, it was decided to analyze only the solutions with a minimum ratio greater than or equal to four. We do not analyze the solutions to unfixed ambiguity or the results that show the absence of daily data in these stations.

On this subset of data, a robust estimation of the "MAD" (median absolute deviation [30]) type was performed for the calculation of the regression line. This analysis occurs if the data of the day just passed are present, but the parameters are calculated without using the latter data. The same

treatment takes place with hourly data. With the estimate of the regression line, for each component, the measure of the coordinate of the last epoch, that is of the day or the hour just passed, is foreseen. The estimate also calculates the robust value of the standard deviation of the data. The current position is considered acceptable and without alarms, if the coordinates are in the range of twice the standard deviation around the value foreseen by the regression line, without the use of the last measures themselves. The signal that is sent to the expert controllers, in this case, is "green traffic light".

In any case, the coordinates are considered acceptable and without alarms, even if they exceed the forecast, increased or decreased by two times their standard deviation, if the displacement is less than a certain tolerance. The tolerances are parametric and are written in a file that also contains a series of variables for statistical analysis. It is, therefore, possible not to use these tolerances but threshold values defined based on the geological study of the phenomenon.

A vector is constructed, which, for the three components, defines a danger index.

If there are no data to be examined, the three components (E, N, h) of the vector are zero.

If there are data to be examined, but the conditions are of "acceptable coordinate" according to the two above criteria, the component of the vector being examined is set to the value 1. This means in practice "green traffic light" or normal conditions.

If, on the other hand, the movement does not meet at least one of the two conditions in the day just passed, the component of the vector in question is set to the value 2. This means in practice "yellow light" or attention level.

The "red light" means that the data would be used in detail as there was both a "yellow light" for the day of the last measure and the day of the penultimate measure. It means that on the last day there was a displacement higher than the allowed one, but also on the penultimate day this happened and the displacement of the last and penultimate day have the same sign. The numeric traffic light index is set to 3, this value can only be present if the value 2 was previously present.

#### 4.2.2 Alert assessment based over a long-term period trend

Another automatic control made by the algorithm is searching for anomalous acceleration trends in a long-term period. In this case, an alarm must be provided if this speed, i.e., the slope of the line, is significantly different from zero.

This check must be performed every day, regardless of whether there are data, not at all or there are no results with a high "ratio." This does not mean that these data are used, but only that the processing is performed in each case and every day.

All series data is used with a ratio value greater than or equal to 4, including the last day.

After having computed the parameters of the trend line with a robust method, the statistical significance of the velocity is calculated using a probability value setting parametrically. This value is set at 90%.

The software procedure, developed in Matlab language, also calculates the absolute value of this speed, using as an index the number of millimeters of displacement every hundred theoretical days of measurement.

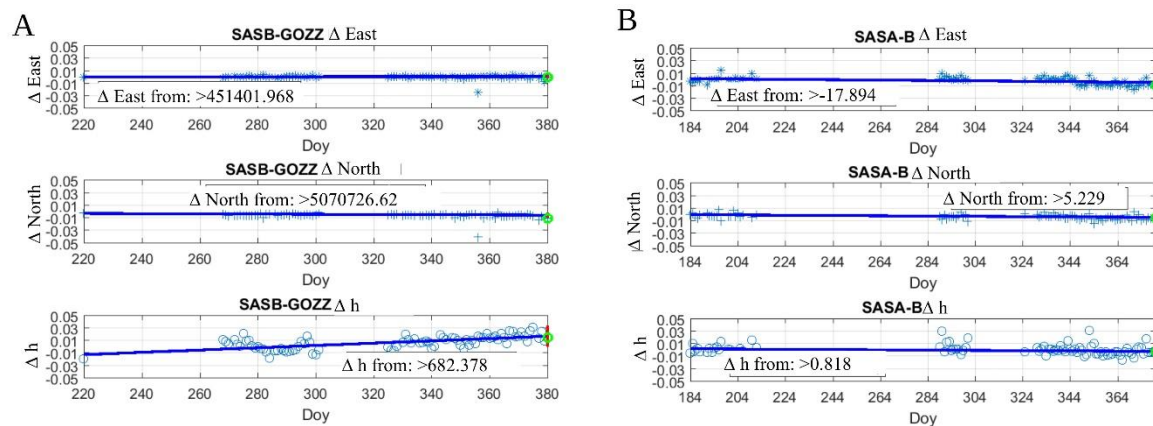
Also, in this case, a vector of three components is written in an output file and, for each baseline, indicates with zero the non-significativity of the estimate speeds. A value not equal to zero, with the sign, indicates the speed in mm/100 days on that coordinate. Any speed that, in absolute value, does not exceed 3 mm / 100 days is considered non-significative, based on the results of topographic monitoring and Colombero studies. Also, this parameter and the probability value of significance are variable parametric indices.

The preliminary results of GNSS monitoring have too short temporal time series to make a reliable analysis. In further studies, it would be possible to make an analysis of the entire seasonal cycle.

**Figure 8** shows an example on the left (Figure 8 A), of some graphs obtained for the movements of one of the two stations of Madonna del Sasso (SASB). In the columns on the right (Figure 8 B), we see the graphs of the deformations between the two stations; both placed on the Madonna del Sasso landslide (SASa-b).

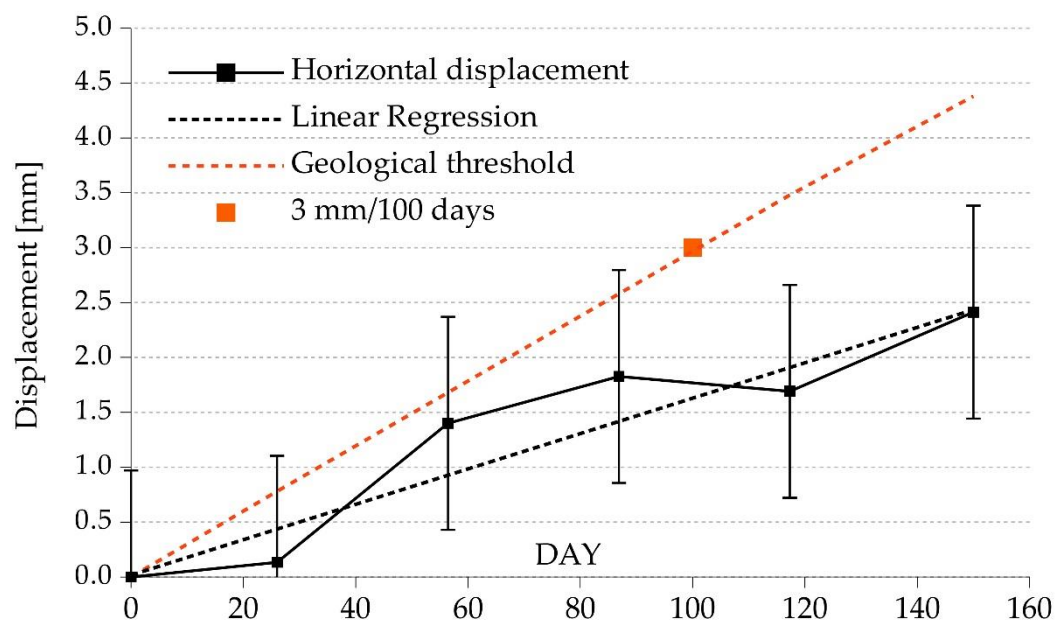
All the graphs are also located daily in the shared Google Drive directory and a daily email that contains the link to a shared cloud directory, sends an ASCII file of the “traffic light” synthesis to geologists specialized in deformation analysis.

The short term analysis of displacement did not show critical acceleration, and the movement is all inside the noise ( $2\sigma$ ) of the measurements. Also, the short term geological threshold was not yet defined as the more extended time series of data is necessary



**Figure 8.** Computation results of the of displacements (left column) and deformations (right column) in meters of Madonna del Sasso registered by GNSS for east, north, and vertical component.

Even long-term displacement has too short temporal series (less than half seasonal cycle) to make reliable interpretation of data. However, a preliminary data processing made on monthly averaged displacement shows a trend that is compatible with historical data and below the geological threshold. It is important to note that noise in the linear regression is higher than the geological threshold, especially during the first months of measurements (Figure 9).



**Figure 9.** Preliminary analysis of GNSS horizontal displacement based on monthly averaged data from December 2018 to May 2019



## 5. Discussion

In this paper, we present the application of a low-cost GNSS system for continuous monitoring of an unstable rock cliff. This case study represents an interesting condition where the deformation trend has been defined using measurements periodically campaigns and different authors studied the dynamic of the slope instability in the last decade. According to the kinematic model of the slope, ARPA decided to check the evolution of the two unstable blocks by semestral topographic campaigns. This control of displacement is enough for the acquisition of new data that can confirm the defined trend or register improvement in the deformation rate. The limit of this approach is the possibility that the slope could change his behavior immediately after a measurement and that a possible dangerous evolution of the instability cannot be detected immediately. The use of continuous monitoring solutions can be a good choice to assure an immediate identification of possible change in the displacement trend, but it requires more effort in terms of cost of installation and management of instrumentation. The cost of continuous monitoring solutions often limited their diffusion, but the rise of new low-cost instrumentations can create the condition for an improvement of diffusion of these systems with a limited improvement of costs.

Many articles recently considered the use of GNSS solution form monitoring purposes. In this paper, we propose not only a technical solution that adopts mass-market instrumentation, but also the definition of a monitoring systems management strategy that can be adopted to GNSS taking into consideration different phases: analysis, validation, interpretation and dissemination of obtained results.

The flowchart of **Figure 10** shows the proposed step procedure that defines the sequence of activities from GNSS raw data to the dissemination of alert status through a dedicated bulletin. This procedure is focused on GNSS data but could be applied to a generic system of monitoring data. The proposed main steps of the monitoring management procedure are:

i) The statistical control of raw data. Using a developed algorithm, only raw data with a minimum acceptable quality pass to the further phase of processing. If the raw data have quality under a defined threshold “ratio test” (**Table 4**), no further elaborations are possible.

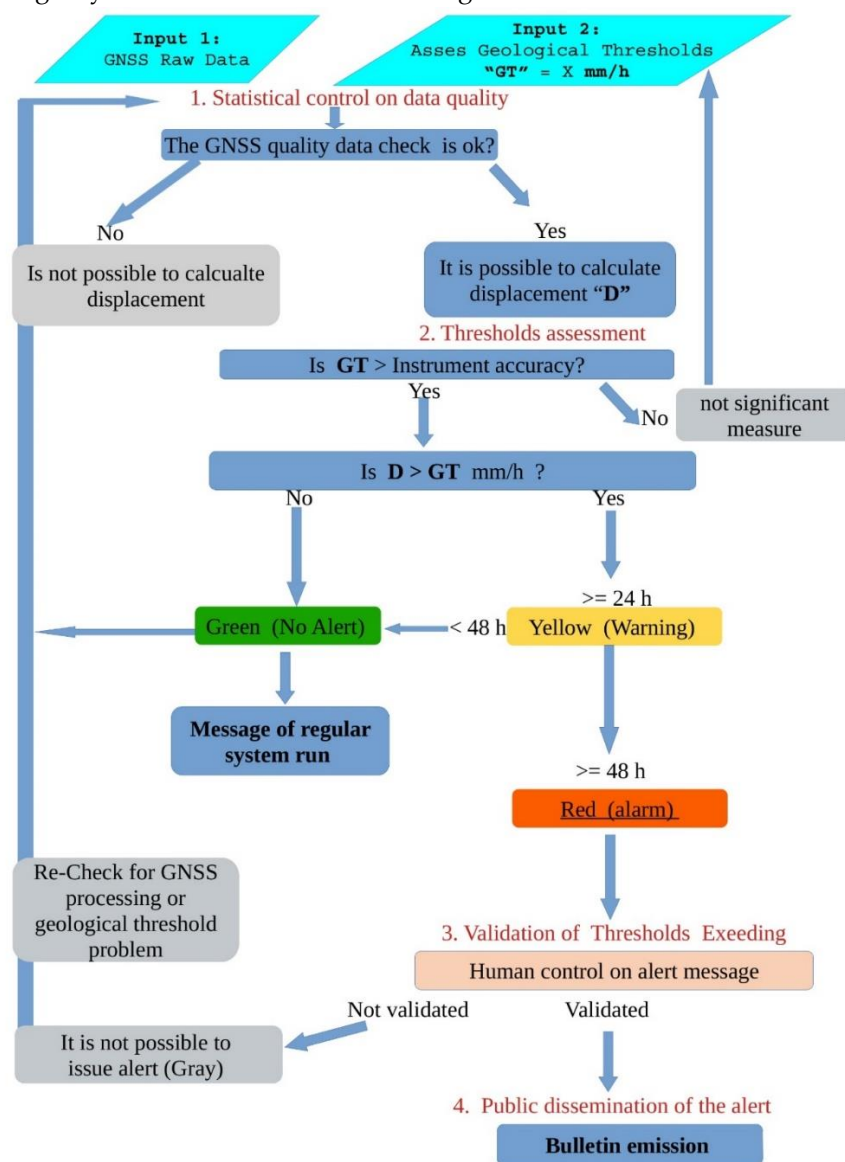
ii) The thresholds assessment. In this step, an automatic algorithm checks if the movement overpasses the statistical and the geological thresholds. The statistical threshold is related to the accuracy of the instrument. The geological threshold is based on the geological model, and it is related to the movement rate that, according to expert studies, could indicate an incipient paroxysm phase. It is important to remark that the geological threshold must be higher than the statistical threshold. If the model shows that the geological threshold is below instrument accuracy, probably our monitoring system is not adequate for the considered slope instability. In the case of Madonna del Sasso, for instance, the geological threshold for short term displacement was not yet determined, but we can consider that it can be very close to the statistical threshold. According to long term monitoring results, the long term threshold is 3 mm/100 days (**Table 5**). This threshold has been defined considering the analysis of long (2006-2019) topographic monitoring sequence. On short period, measures that overcome the statistical threshold have to be carefully considered to check if this result can be considered a spike or the beginning of a critical phase, for this reason, the system required a double validation of first warning to declare an alarm: once the monitoring result has been statistically validated, it should be analyzed and validated also from the geological point of view.

If the displacement is higher than the statistical threshold, an automatic warning report is generated: the procedure considers, as usual, three levels of warning: a) green light that means regular conditions (i.e., the geological thresholds is not overpassed; b) yellow level (warning), if the statistical threshold have been overcome for the first time. In this phase, we can also consider the possibility that it could be an error in the system and, for this reason, we have to wait for the second cycle of measurement to obtain a validation of the trend, c) if the second cycle validates the result of the previous one, we can be sure that the result is correct and we are in third level (alarm) condition. In this condition, monitoring results should also be evaluated and validated from the geological point of view. This procedure has been implemented to be totally automatized and requires the human check only at the end of a quality control procedure, for the last validation of the alert.

**Table 5.** The threshold used for Madonna del Sasso.

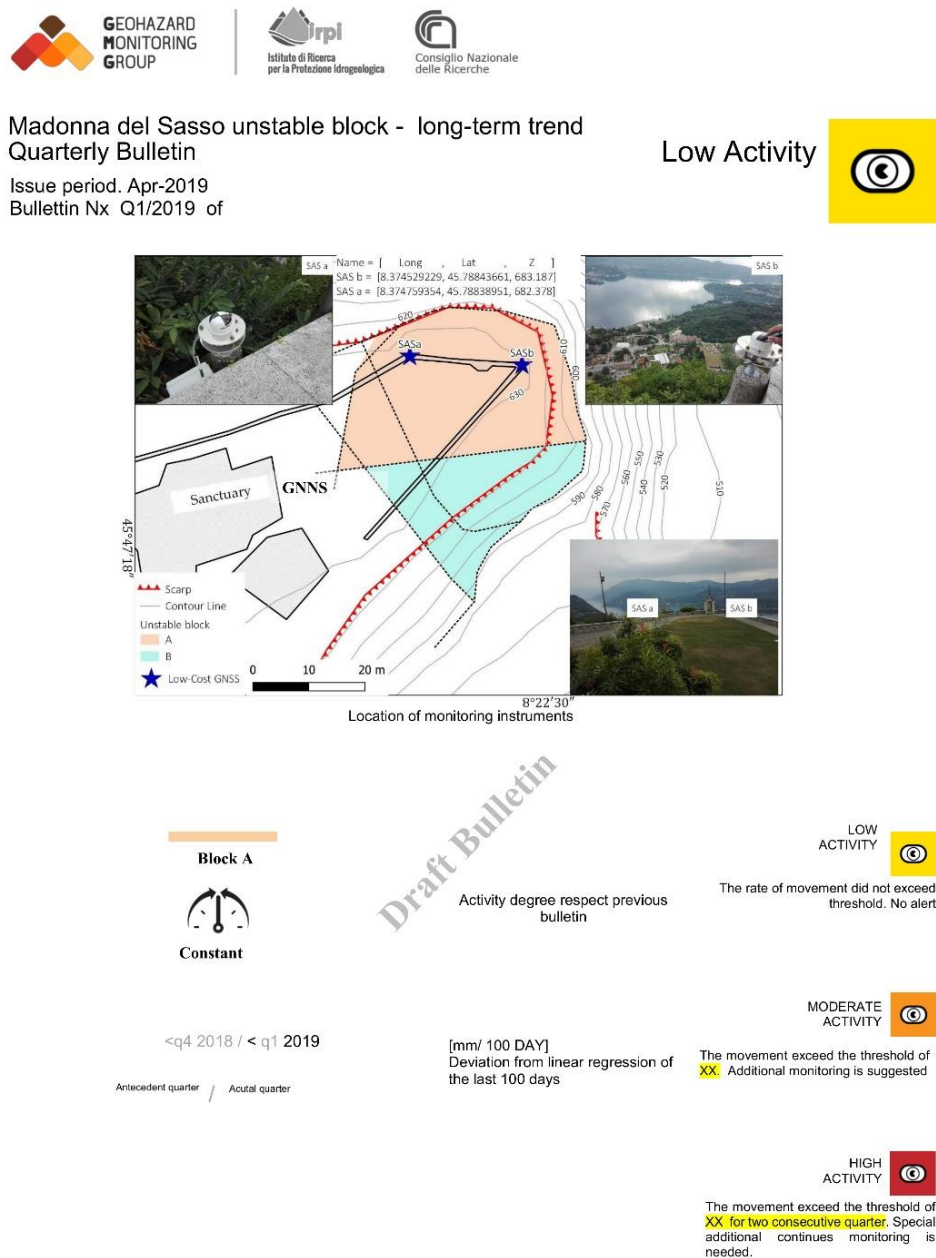
Displacement type	GNSS Data quality (ratio test)	Statistical thresholds	Geological thresholds
Short term (Hourly to daily)	>4	$\geq 2\sigma + 5 \text{ mm}$	Not yet determined
Long term (Monthly to semester)	>4	$\geq 2\sigma$	>3 mm/100 days ( $\approx 11 \text{ mm/yr}$ )

iii) The validation of the alert. This is a human-based procedure in which experts, on the base of automatic alert messages that coming from the monitoring systems, decide the congruency of the alert messages and they activate alert communication procedure to the authorities and the public. This step can be done using a single monitoring system, but a complex monitoring network based on redundant instruments is usually suggested. In this phase, the contextual use of data from the monitoring system and the operative monography can support decision-makers in the evaluation of the level of emergency and the definition of risk mitigation activities.



**Figure 10.** Flowchart of the proposed procedure to define and test the alert threshold based on continuous and low-cost GNSS monitoring. The chart is focused on daily processing, but the same schema could be applied to long-term thresholds

iv) The alert bulletin dissemination. If the alert has been validated, the implemented system can update a dissemination bulletin aimed to inform the population about the last monitoring results and the level of activity of the considered phenomenon. According to [31], this bulletin can be redacted manually or automatically from a pre-defined model adapted to the monitored phenomenon. With the proposed approach, the bulletin can be disseminated only when a robust monitoring system supports an alert, and monitoring results have been geologically validated. An example of the dissemination bulletin dedicated to the Madonna del Sasso case study is presented in **Figure 11**.



**Figure 11.** A draft of the possible quarterly bulletin to disseminate information about the long-term trend behavior of the unstable block. Modified from [31]

6. Conclusions

The use of GNSS low-cost systems is nowadays a possible solution for in situ continuous monitoring applications aimed to control the evolution of slope instabilities. The use of the low-cost system should be carefully evaluated and validated firstly for the technological and geodetic point of view, considering that the quality of measures and their accuracy are compatible with the entity of displacement that characterized the monitored instability. The GNSS low-cost solution can be particularly interesting when we have to control the evolution of low rate slope instabilities that could be affected by a sudden increment of displacement that can be considered the precursory of a failure. According to this scenario, a periodical monitoring approach can be not enough to identify a change in the displacement trend immediately.

The Madonna del Sasso case study represents a good example of this scenario. According to ARPA monitoring system results, we know that this site characterized by an annual trend of 2 mm/yr. The ARPA monitoring network can be considered a good solution for the control of the evolution of the studied area but the frequency of measurement campaigns, of course, could be too limited to recognize immediately the possible change in the displacement trend that is an important information for a correct evaluation of the stability condition of the rocky cliff. The use of the proposed GNSS low-cost monitoring network can be considered a good solution to improve the acquisition rate with a low impact on the overall effort required for the control of the stability of the cliff. The installed low-cost GNSS receivers have shown similar performance in terms of accuracy and precision respect geodetic GNSS. Considering that the cost is ten times lower, the precision decreases not significantly.

With the completion of the new satellite constellations (e.g., Galileo), the improvement of the processing hardware and software, can be expected to reduce costs and increase monitoring accuracy. The simple installation of GNSS is not sufficient to obtain a good monitoring system able to limit the impact of management costs. For this reason, we also implemented a methodology that is based on an automated procedure able to control the correct running of the system and the quality of results. The automatized procedure checks if the obtained results are statistically correct, and if the displacement trend exceeded predefined thresholds. The low-cost GNSS should have a central role in making continuous and dense monitoring that, in case of paroxysm phases, could be temporally implemented by high-precision instruments. This approach has the aim to make affordable the constant monitoring of many sites today monitored only with discontinues instrumentation. The last phase of the proposed methodology also considers the emission of the alert bulletin.

The improved procedure automatically checks the quality of measurement session results and it compares results with pre-defined thresholds, but has been developed for considering a final human check and geological validation. The final validation is done using the operative monography, a document designed to highlight what we already know about the studied slope instability and possible evolutions. The final check done by experts is necessary to have reliable data, especially when the geological model of the unstable slope is not well known.

We set up the presented methodology considering the Madonna del Sasso case study. This site has an important dataset acquired in last decades by different research groups. Available information have been summarized in an Operative Monography (OM). The primary outcomes of literature studies and the analysis of the non-continuous monitoring system of ARPA Piemonte were collected and analyzed. According to OM results we chose the best location for the installation of the low-cost GNSS system and we fixed the preliminary geological alert thresholds.

**Author Contributions:** Conceptualization: **Davide Notti, Alberto Cina and Daniele Giordan**; Data curation: **Davide Notti, Ambrogio Manzino, Alessio Colombo**; Formal analysis: **Ambrogio Manzino**; Investigation: **Davide Notti, Alberto Cina and Daniele Giordan**; Methodology: **Alberto Cina and Daniele Giordan**; Project administration: **Alberto Cina, Paolo Mollo and Daniele Giordan**; Funding acquisition: **Alberto Cina**; Resources: **Iosif Horea Bendea and Paolo Mollo**; Software: **Alberto Cina, Ambrogio Manzino, Iosif Horea Bendea and Paolo Mollo**; Supervision: **Alberto Cina and Daniele Giordan**; Validation: **Ambrogio Manzino and Iosif Horea Bendea**; Visualization: **Davide Notti**; Writing – original draft: **Davide Notti**; Writing – review & editing: **Alberto Cina and Daniele Giordan**.

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development activities on technologies and instruments of geomatics for the monitoring of landslides and infrastructures)".

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