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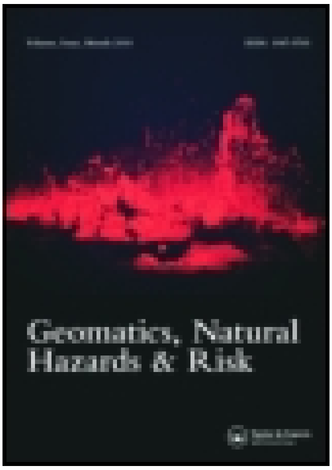

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Real-time monitoring for fast deformations using GNSS low-cost receivers

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Letter

Real-time monitoring for fast deformations using GNSS low-cost receivers

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Landslides are one of the major geo-hazards which have constantly affected Italy especially over the last few years. In fact 82% of the Italian territory is affected by this phenomenon which destroys the environment and often causes deaths: therefore it is necessary to monitor these effects in order to detect and prevent these risks. Nowadays, most of this type of monitoring is carried out by using traditional topographic instruments (e.g. total stations) or satellite techniques such as global navigation satellite system (GNSS) receivers. The level of accuracy obtainable with these instruments is sub-centimetrical in post-processing and centimetrical in real-time; however, the costs are very high (many thousands of euros). The rapid diffusion of GNSS networks has led to an increase of using mass-market receivers for real-time positioning. In this paper, the performances of GNSS mass-market receiver are reported with the aim of verifying if this type of sensor can be used for real-time landslide monitoring: for this purpose a special slide was used for simulating a landslide, since it enabled us to give manual displacements thanks to a micrometre screw. These experiments were also carried out by considering a specific statistical test (a modified Chow test) which enabled us to understand if there were any displacements from a statistical point of view in real time. The tests, the algorithm and results are reported in this paper.

1. Introduction

Landslide is defined as "the movement of a mass of rock, debris or earth down a slope" (Cruden 1991). In recent years some landslide disasters (in Brazil, Philippines, Indonesia, Pakistan, etc.) have destroyed infrastructure, killed thousands of people, and resulted in heavy economic losses (USGS 2013). The continuous occurrence of disastrous landslide events has increased the demand for new and improved techniques for landslide monitoring and analysis (Eyo Etim et al. 2014).

Geomatic techniques and instruments such as total stations, laser scanners and GNSS receivers are often used for monitoring deformation events either by integrating these methods with one another or by considering them individually.

For example, GNSS receivers and antennas have been employed in landslide monitoring both in periodic (Yalçinkaya & Bayrak 2002; Rawat et al. 2011; Wang 2012) and continuous (Wang & Soler 2012; Xiao et al. 2012) ways. In landslides monitoring some critical factors such as accuracy, instrumentation cost and safety of equipment must be considered in function of dangerousness and safety of people and infrastructure. In

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*Corresponding author. Email: paolo.dabove@polito.it order to do this some studies in landslide monitoring have used GPS/GNSS to compare results from conventional surveying or geotechnical methods, such as theodolite, electronic distance measurement, levels, total station (Rizzo 2002), inclinometers (Calcaterra et al. 2012) and wire extensometers (Gili et al. 2000; Moss 2000; Malet et al. 2002; Coe et al. 2003; Tagliavini et al. 2007; Bertachini et al. 2009). In other studies global positioning system (GPS) instruments were integrated with other surveying techniques, such as terrestrial laser scanning, synthetic aperture radar (SAR) interferometry (Rott & Nagler 2006; Peyret et al. 2008) and photogrammetry (Mora et al. 2003), to investigate the landslide phenomenon (Wang 2011). Some studies have also investigated the accuracy of low-cost single-frequency GPS receivers for landslide monitoring (Squarzoni et al. 2005) both in post-processing (Dabove et al. 2014; Cina & Piras 2014) and in real-time approach in order to analyse the various types of landslide phenomena. In both cases, the greatest peculiarity of these instruments is that they provide a centimetre or sub-centimetre accuracy in real time when the fixing of the phase ambiguity is carried out, also considering different GNSS positioning techniques (Othman et al. 2011a, 2011b) such as static (Brunner et al. 2007), rapid-static (Hastaoglu & Sanli 2011) and real-time kinematic (RTK; Wang 2011) positioning.

NRTK (network real-time kinematic) positioning (Günther et al. 2008; Heunecke et al. 2011) is possible when geodetic instruments are used (figure 1) but these

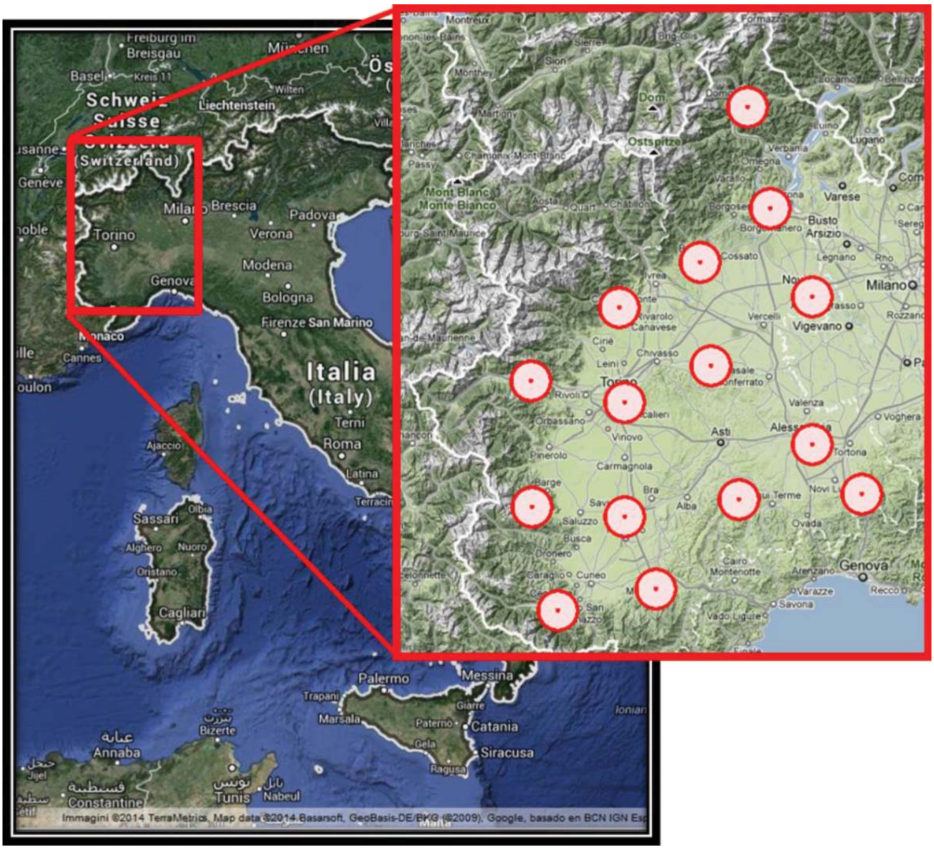

Figure 1. The GNSS NRTK network of Regione Piemonte used in these tests.

instruments cost about €5000 which is a lot of money considering that they can be lost or damaged in the event of a landslide. Moreover, more than one instrument is required for monitoring purposes causing a further increase in costs and in probability of damages.

The aim of this study is to analyse and illustrate the use of GNSS mass-market instrumentation and its limitations in order to monitor real-time geological instability events such as slow-moving landslides by means of an innovative statistical approach.

These instruments were chosen due to the fact that this type of receiver and antenna can be considered to be disposable instrumentation thanks to their cheapness, but they are also able to achieve centimetric accuracy by filtering the measurements carefully as described in the follow sections. Moreover, thanks to the NRTK positioning, they allow us to obtain a similar level of accuracy with respect to GNSS geodetic instrumentation (Manzino & Dabove 2013).

2. Landslide analysis considering GNSS mass-market instruments

As already mentioned, in order to lower the costs and the probability of losing these instruments, both mass-market receivers and antennas were considered. The evaluation kit costs about €350 and includes a single-frequency (L1) receiver and a magnetic antenna: for this test we used a u-blox EVK-5T (http://www.u-blox.com/en/lea-5t.html) receiver with an external antenna (Garmin GA29F) (table 1) which costs

Table 1. Characteristics of GPS receiver and antenna used in this test.

Mass-market receiver LEA–EVK-5T	Mass-market antenna Garmin GA29F
	
Constellation: GPS Data: L1 C/A and phase, Doppler, S/N Rate: 0.25–1000 Hz Correction type: RTCM 2.x, 3.0, SBAS, Assist Now online & offline Cost: about €350	Gain: 27 dB on average Cost: about €40

around €40. This choice was made because, in previous tests (Manzino & Dabove 2013), this type of antenna has proved to have a better signal to noise ratio and therefore provided a good quality of the GNSS signal.

Three conditions are required in order to achieve the same levels of accuracy with mass-market receivers as with the geodetic ones: a good quality of pseudo-range and carrier-phase signals on the GPS L1 frequency (which is the only available frequency with the u-blox receiver), a good modelling of the GNSS biases by the CORS (continuous operating reference station) network which is also suitable for single-frequency receivers and a network software that allows for a reliable fixing of the phase ambiguity in real time.

However, positioning with these receivers is slightly noisier than when performed with geodetic receivers: for this reason, special filtering and tests are required to determine whether a notable shift has occurred or not. The calibration of the antennas used for these purposes is not a critical issue because the major goal is to monitor the displacements/deformations with respect to existing positions.

3. The level of precision and accuracy obtained with a mass-market receiver

Before using these mass-market instruments for monitoring purposes, it is essential to check the levels of precision and accuracy obtainable in real time: this is done by carrying out an NRTK positioning on a stable location with known coordinates estimated with high accuracy.

The experiments were carried out by using a pillar located on the roof of the headquarters of the Politecnico di Torino at Vercelli as rover site with the same receiver and the same antenna for 24 hours consecutively with an acquisition rate equal to 1 s, considering the VRS® correction provided by the Regione Piemonte NRTK network (figure 1– http://gnss.regione.piemonte.it/frmIndex.aspx).

Figure 2 shows the trend of the planimetric dispersion (Δ2D) of the positioning obtained with the fixed phase ambiguity. It is important to note that in 24 hours, 95% of the positions have an error less than 5 cm if more than six satellites are observed. This is a good result if we consider the fact that the nearest CORS was about 20 km far from the rover; this accuracy is not useful for landslide monitoring but the performances are better if the distance between CORSs and rover decreases or if a network differential correction is sent to the rover, as it is possible to see in the next sections. Regarding altimetric errors, some previous tests (Cina & Piras 2014) were made: these have demonstrated that the accuracy is about 5 cm and that it not useful for this type of application. Also this aspect will be investigated in this paper in order to show the three-dimensional performances of this type of receivers for landslides monitoring.

4. The test performed

A special device has been developed and built at the Laboratory of Topography of the Politecnico di Torino – DIATI Department in order to simulate landslide displacements in the most accurate way.

This device is composed of a series of calibrated steel bars with special screws which enable us to give horizontal and vertical displacements of the GNSS antenna with micrometric accuracy. The movements are set by means of a hand-wheel which

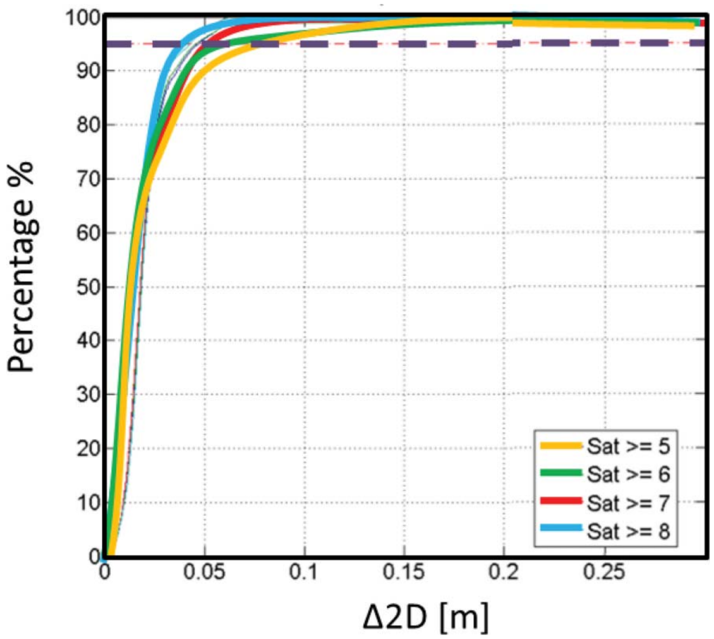

Figure 2. Planimetric dispersion (Δ2D) of NRTK positioning considering the VRS® correction with respect to the correct position obtained in post-processing.

moves the slide along the rail: it is therefore possible with a millimetre tape to obtain direct and visual information of the movements in order to compare the imposed movements against those measured by GNSS instruments. With this slide, we are able to make horizontal and vertical movements up to 1.30 and 1 m, respectively.

By means of other special mechanisms, it is possible to rectify the slide in order to obtain a precise movement definition along the steel bars. As stated in a previous study (Cina & Piras 2014), there is always a precision of the slide movement of about 1 mm: therefore it is possible to state that this value is considered as the “scale resolution” of this support.

The patch antenna was mounted on this slide as shown in figure 3. Also in this case the experiments were carried out using these mass-market receivers within the Regione Piemonte NRTK network, considering a VRS® stream broadcast by the SpiderNet network software of the Leica Geosystems® Company.

The positioning results were obtained with a frequency of 1 Hz, considering displacements equal to 1 cm both in planimetry and in altimetry which were provided manually every 30 seconds.

RTKLIB V. 2.4.2 routines were used in order to carry out the NRTK positioning, that is to succeed in determining the phase ambiguity in real time.

RTKLIB (http://www.rtklib.com/) is an open source program package for GNSS standard and precise positioning and is distributed under a GPLv3 licence. This software supports standard and precise positioning algorithms with GPS, GLONASS and QZSS constellations in addition to a satellite based augmentation system (SBAS) correction. Furthermore, it supports various GNSS positioning modalities for both real-time and post-processing approaches: single-point, differential global positioning system/differential global navigation satellite system (DGPS/DGNSS), kinematic, static,

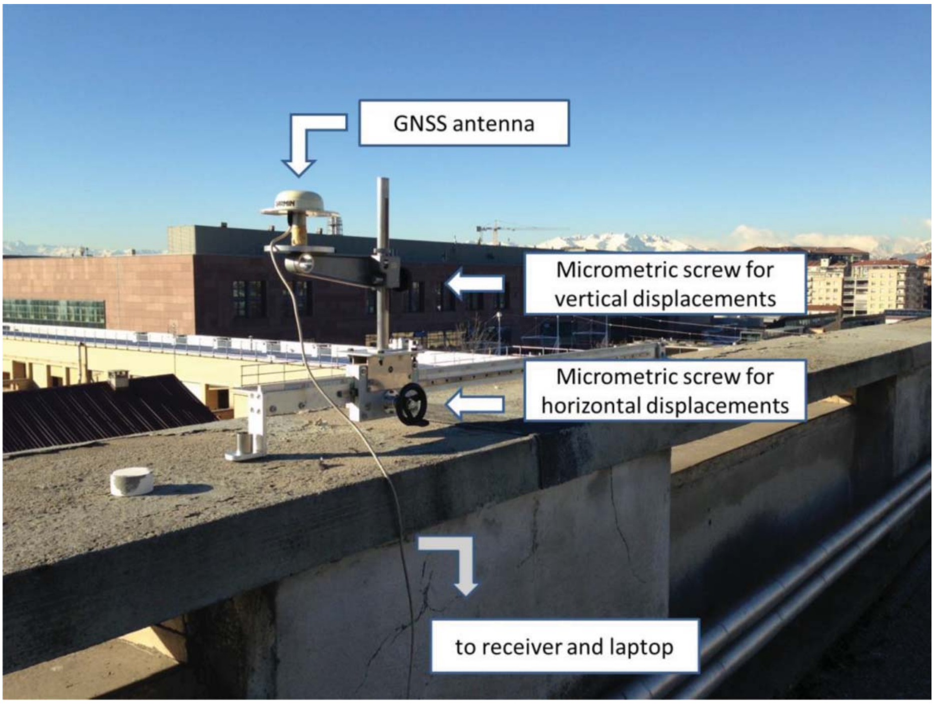

Figure 3. The slide where the GNSS antenna was mounted.

moving-baseline, fixed, etc. It supports both several GNSS receiver proprietary messages, e.g. u-blox (LEA-4T, 5T, 6T) and an external communication via serial, transmission control protocol/internet protocol (TCP/IP), networked transport of RTCM via internet protocol (NTRIP), etc. The RTKNAVI tool, one of the RTKLIB routines, was used for carrying out the experiments. This tool enables us to provide as input both the raw data (GNSS pseudo-range and carrier-phase measurements) of the u-blox receiver and the stream data coming from a network with NTRIP authentication (http://epsagnss.usal.es/documentos/ntripdocumentation.pdf). For this reason the receiver was connected to a laptop through which it was possible to connect to the Internet.

The software allows the RTK positioning and fixing the phase ambiguities, even if the receiver uses the single frequency L1.

5. The statistical tests used in the analysis of the displacements

The Chow test is a statistical test which determines whether the coefficients in two linear regressions on different data sets are equal. This test was invented by a homonymous economist in 1960 (Chow 1960; Dougherty 2007): in econometrics, the Chow test is most commonly used in time series analysis to test for the presence of a structural break, but it is not suitable for analysing data series in real time. This is due to the fact that three contemporary scenarios have to be investigated: this procedure is not available in real time because no time series are obtainable, as it is possible to see from equations (1)–(3).

Let us presume to have a time series with a structural break: meaning that there is a clear variation over time of the regression parameters.

If we lead a single regression, the result would be to obtain a good report on average. The Chow test checks if this break exists and, if so, whether it is significant or not.

Suppose that the displacement model (*d*) of our data is

$$d(t) = a + b \cdot t + \varepsilon \tag{1}$$

If our data are divided into two groups, then we obtain

$$d_1(t) = a_1 + b_1 \cdot t_1 + \varepsilon_1 \tag{2}$$

$$d_2(t) = a_2 + b_2 \cdot t_1 + \varepsilon_2 \tag{3}$$

for the first and second groups, respectively.

The null hypothesis of the Chow test asserts that $a_1 = a_2$ and $b_1 = b_2$. There is the assumption that the model errors $\boldsymbol{\varepsilon}$ are independent and identically distributed from a normal distribution with unknown variance. Under the previous hypotheses, the test statistic *C*, which follows *F*-distribution, is given by

$$C = \frac{\frac{S_c - (S_1 + S_2)}{k}}{\frac{S_1 + S_2}{n_1 + n_2 - 2k}} \sim F^{\alpha}_{k, n_1 + n_2 - 2k} \tag{4}$$

where n_1 and n_2 are the numerousness of these two groups, k is the number of parameters of the model, while S is the sum of the squares of the residuals (S_1 for the first group, S_2 for the second one and S_c for the joint groups). This value, obtained by means of the Chow test, follows the Fisher distribution with k and $n_1 + n_2 - 2k$ degrees of freedom. The C value is compared with the percentile $F^{\alpha}_{k,n_1+n_2-2k}$ (where α means the confidence interval in percentage) and the null hypothesis is not rejected if $C < F^{\alpha}_{k,n_1+n_2-2k}$. Chow test can be derived, as a special case, by the testing of the general hypothesis that is widely applied by the geodetic community, where a linear parametric model is compared with the corresponding constrained one (some linear constraints on the parameters have been added) (Koch 1987).

As previously said, the Chow test is most commonly used in post-processing approaches in order to test if a structural break is done. In this paper, we want to modify this test in order to use this in real time; equation (1) is modified as follows:

$$\begin{aligned} X_i &= X_{i-1} + (t_i - t_{i-1}) \cdot v_x \\ Y_i &= Y_{i-1} + (t_i - t_{i-1}) \cdot v_y \\ Z_i &= Z_{i-1} + (t_i - t_{i-1}) \cdot v_z \end{aligned} \tag{5}$$

with a constant velocity model. The constant velocity in the case of no landslide occurs would be either zero, or constant, in which case it reflects not so much the effect of plate rotation, but rather seasonal variations, mainly a quasi-periodic annual signal, which appears to be linear within the small duration of the experiment. So, if no landslide occurs, the velocities v_x, v_y, v_z are equal to zero: this means that the difference of coordinates between two consecutive epochs is quite equal to zero, short of the measurement noise. The goal is to identify the displacements that occur in a certain epoch if we started from a sample of coordinates without displacements; the steps of our procedure can resume as follows:

- we choose a dimension of a sample (n);
- we start considering this sample composed of differences of coordinates (which in this case are east, north and up in metres) between the epoch $t-n$ and t: for example, if we assume to consider only the Z coordinate, the sample will be composed as $\begin{bmatrix} Z_{t-3} \\ Z_{t-2} \\ Z_{t-1} \\ Z_t \end{bmatrix}$ and the residual S is $\begin{bmatrix} Z_{t-3}-Z_{t-2} \\ Z_{t-2}-Z_{t-1} \\ Z_{t-1}-Z_t \end{bmatrix}$ if $n=4$. The hypothesis is that no displacements are present in this sample;
- we add another element of this sample, obtained at the epoch $t+1$, and we delete the oldest observation from this sample, which now will be composed as follows: $\begin{bmatrix} Z_{t-2} \\ Z_{t-1} \\ Z_t \\ Z_{t+1} \end{bmatrix}$ while the residual vector is $\begin{bmatrix} Z_{t-2}-Z_{t-1} \\ Z_{t-1}-Z_t \\ Z_t-Z_{t+1} \end{bmatrix}$;
- we compare the result obtained at epoch t with those obtained at epoch $t+1$: if according to the modified Chow test, so if $C < F^{\alpha}_{k,n_1+n_2-2k}$, we can state with a risk α that there is no displacements, otherwise a displacement occurs; if we are in the first case, we can continue to both consider new epochs and perform the modified Chow test, while in the second case we stop the procedure and we restart all, considering a new initial sample in which the oldest epoch is the first one after the identified displacement.

A schema of this approach can be found in figure 4. In this paper, all the three components (X, Y, Z) are considered: it is possible to affirm that between the [X_i Y_i Z_i] observations (that are estimates) at every single epoch t the correlation exists. This is mainly due to the fact that the var-covariance matrix of the solutions is not diagonal because all three parameters (X, Y, Z) are the result of only one system. A correlation between estimates at different epochs also exists, but it may be neglected in a first approximation. In this case we know that performing the Chow test in every

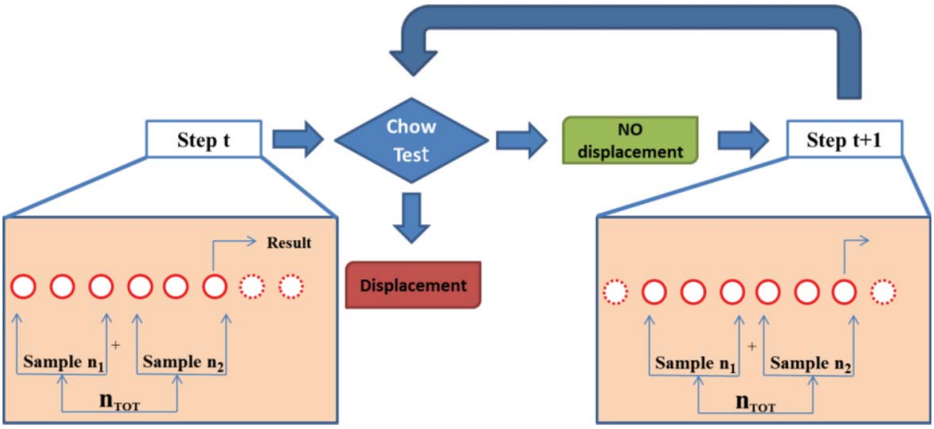

Figure 4. The modified real-time Chow test approach scheme.

coordinate time series separately is not the statistically optimal but we want to verify if, despite this, good results can be obtained. A multidimensional (three-dimensional) version of the modified Chow test will be developed in future. As we can see in equation (5), one of the parameters which must be provided as input is the size of the sample: various tests were carried out by choosing a number of samples equal to 3, 4, 5, 10 and 15 elements in order to assess which sample size can be significant in terms of both correct prediction and number of false alarms.

The modification in size also causes a change in the reference values in Fisher's table with interval of significance $\alpha = 10\%$ (the value used in figure 6, for $n_1 = n_2 = 10$ and $k = 1$ because we consider a horizontal line, is 3.01, represented in green). We have adopted this value because we want to identify the movement surely. Obviously if the displacements are bigger than 1 cm (e.g. 2 or more cm) the result does not change: the displacements are however identified and the algorithm stays valid.

In order to adapt the test to the real-time approach, the samples were chosen according to the following schema, like a sliding window through time:

A number of contiguous samples in time and size ($n_1 = n_2$) were analysed for each period of time: in the next period both samples shift (by 1 second) through the time scale and equation (4) is re-calculated.

6. Data processing, results and analysis

The method previously described is applied to a real case that simulates a landslide: as previously said, the system was composed as shown in figure 3 and the positioning results were obtained with a frequency of 1 Hz, considering displacements equal to 1 cm both in planimetry and in altimetry which were provided manually every 30 seconds, as is possible to see in figure 5.

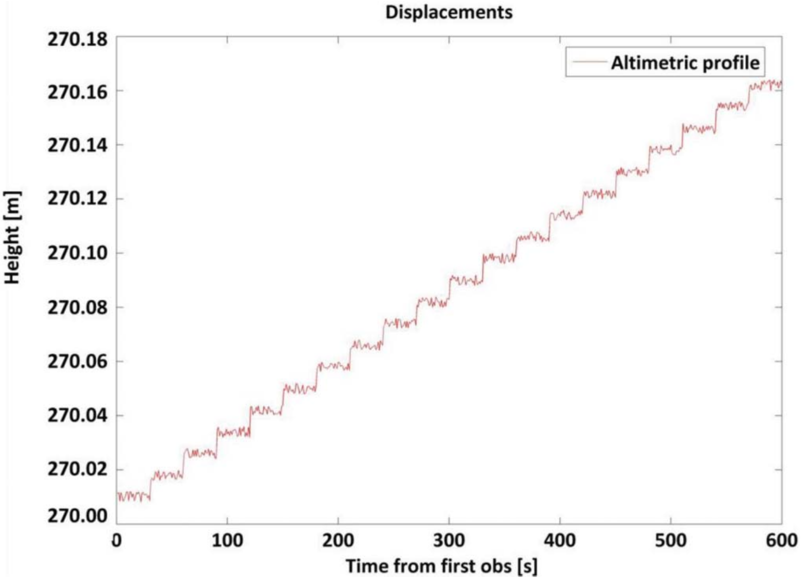

Figure 5. Analysis of displacements provided manually (only up component).

Table 2. Results of Chow test.

No. of sample elements ($n_1 = n_2$)	Displacements detected (%)	Displacements *not* detected (%)	Detected incorrectly/ total detected (%)
"3"	81.8	18.2	31.0
"4"	90.0	10.0	25.0
"5"	83.0	17.0	25.5
"10"	93.1	6.9	3.3
"15"	86.2	13.8	0.0

Regarding the Chow test, we decided to consider a sample with different dimensions in order to determine the "best" number of elements for detecting discontinuities already mentioned. Table 2 shows the results of the Chow test obtained with a sample of various dimensions.

For example, with the number of sample's elements equal to 4 we have obtained 20 displacements: 18 were detected correctly, 2 were not detected and 5 were detected incorrectly. So in table 2 in the second column it is possible to find 90% (as 18 × 100/20), in the third one 10% and the last one 25%.

By analysing table 2 it appears that the greater the number of samples, the higher the probability of passing the test.

Another important aspect is to check for "false positives": in fact the number of elements included in the sample must be calibrated both in order to minimize false alarms and to limit the time latency of the alarm.

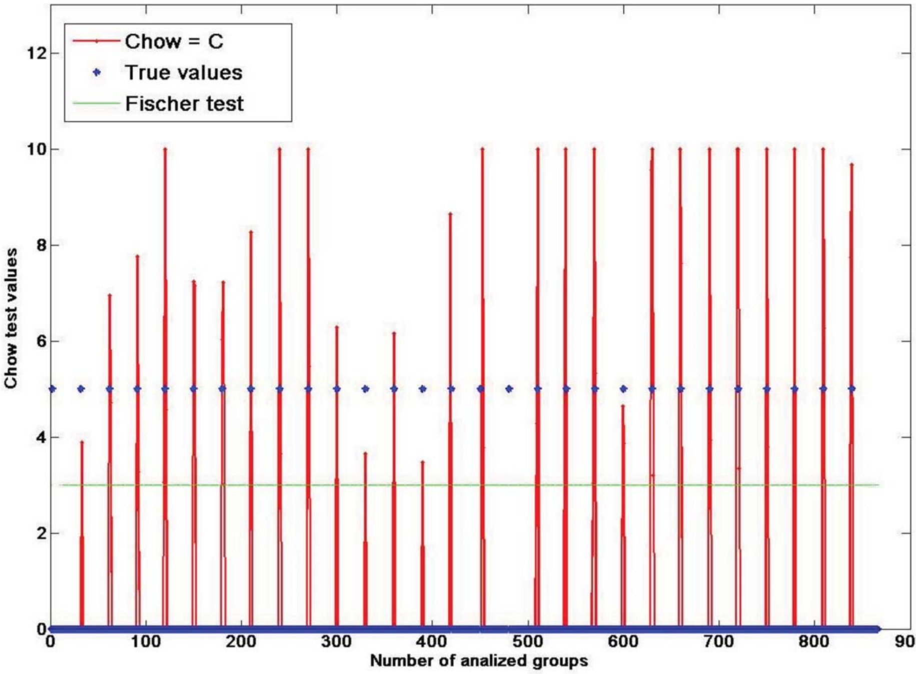

Figure 6. A zoom of Chow test results for $n_1 = n_2 = 10$. To view this figure in colour, please see the online version of the journal.

By considering numerous previous tests, it is possible to affirm that the sample including 10 elements probably represents the best compromise between the detection of the discontinuities and the so-called *false alarms* (detected incorrectly/totally detected) which can be seen in figure 6, where the results of the Chow test are presented in red (C value in equation (4)) and the "true" discontinuities are presented in blue. The sample with 10 elements can be considered better than the one with 15 elements because it presents a less number of not detected displacements even if it presents a greater number of incorrectly detected displacements.

7. Final remarks and conclusions

According to the results obtained from these experiments, these instruments and statistical methods can be useful tools for studying and detecting landslide displacements using GNSS instrumentation. A 1-cm precision level (the magnitude of imposed displacements) can be obtained in real time with inexpensive instruments costing a mere few hundred euros.

Regarding the Chow test, according to the previous results it is possible to state that a 10-element sample size (meaning that a sample composed of 10 epochs = 10 seconds of latency of alarm at 1 Hz of acquisition rate) represents the best combination: it enables us to correctly identify 93.1% of the displacements with a very low rate of false alarms equal to 3.3%. It must be underlined that these results are not generalizable: in this paper the goal was to identify a statistical tool useful to discover displacements in real time, considering a modified version of the Chow test's approach. The previous percentages are rough guide values that are the results of the performed tests.

These data were analysed by considering a sudden motion even if it is possible (although more complex in the check phase) to apply the Chow test in the case of movements with variable speed. As previously said, the modified Chow test is applied in this paper in every coordinate time series separately: this is not the statistically optimal but goal was to verify if good results can be obtained despite that. The next step of this work is to implement a multidimensional (three-dimensional) version-extension of the modified Chow test that it will be developed in future.

In these cases the same results should be analysed by means of the Kalman filter which allows for an even more complex insertion of laws motion. This will be the subject of subsequent investigations.

By using these receivers on a landslide site, the total cost of receiver, antenna, the transmission system and power supply (solar panel and battery) is less than €600. The advantage is that it is possible to calculate the position of the receivers in a similar way to the CORS network, with obvious advantages in the precision and accuracy of the results and the landslide analysis.

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