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Safety – Sentinel for geohazard prevention and forecasting

Deliverable D.F1: Validation procedures

A deliverable of

Task F: Product validation

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Lead contractor for this deliverable: IGME
Partners: CDCP, IDPC, CNIG-IGN, UNIFI

Dissemination Level		
PU	Public	
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the Consortium (including the Commission Services)	
CO	Confidential, only for members of the Consortium (including the Commission Services)	
TN	Technical Note	X

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EXECUTIVE SUMMARY

SAFETY is a two-year research project funded under the ECHO (European Commission's Humanitarian aid and Civil Protection department) call "Prevention and preparedness projects in Civil Protection and marine pollution", which started the 1st January 2016. The mission of the project is to improve the efforts in detecting and mapping geohazards (i.e. landslides and subsidence), by assessing their activity and evaluating their impact on built-up areas and infrastructures' networks. SAFETY will enhance ground deformation risk prevention and mitigation efforts in highly vulnerable geographic and geologic regions. The outcomes of the project will provide Civil Protection Authorities (CPA) with the capability of periodically evaluating and assessing the potential impact of geohazards on the selected sites.

The validation of the SAFETY products will be based on three pillars:

(1) To critically assess the software developed tools.

(2) To validate the results obtained on the two test sites of the project;

(3) To evaluate the usefulness of integrating SAFETY products into CPA prevention activities.

This will provide a fundamental contribution to prove the technical soundness of the proposed products and thus increase their acceptability. The technical acceptability of innovative products, like those proposed in this project, is an essential component to guarantee an effective implementation of the SAFETY procedures in the workflows of the CPAs.

The Action F.1 consists on the Definition of the validation procedures, that is the general criteria and the procedures adopted to validate SAFETY products. They will be decided based on the inputs from task D.B1 "User Requirements and Assessments", updated on 31st May 2016.

The present technical note D.F1 describes the specific validation procedures to be executed in both the selected test sites: the Volterra area (Italy) and the Canary Islands (Spain).

Responsible for implementing it: IGME.

Participants: CDCP, IDPC, CNIG-IGN, UNIFI.

Safety

REFERENCE DOCUMENTS

N°	Title
RD1	DoW, Part F
DB1	User needs and requirements

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INTRODUCTION

The project Safety aims to provide to the Civil Protection Authorities (CPA) the capability of periodically monitor and assess the impact of geohazards (landslides and subsidence, volcanos, earthquakes) on urban areas. The project's objectives are to improve the ability to detect and map landslides, to assess and forecast the impact of triggered landslide events on vulnerable elements, and to model landscape changes caused by slope failures. Safety is mainly addressed to the CPAs at different administrative levels.

This document describes the specific validation procedures to be executed in both the selected test sites, the Volterra area (Tuscany region, Italy) and the Canary Islands (Spain), taking into account the identification of the products required by user needs (Deliverable DB1, User requirements). The document will be divided into two main parts, regarding the test-sites:

(1) Validation procedure for the Volterra area (Tuscany region):
   a. Geo-hazard susceptibility map validation in the Volterra municipality,
   b. Geo-hazard activity map on the roads SR68 and SP15.
(2) Validation procedure for the Canary Islands:
   a. Rockfall hazard validation along the GC-200 road,
   b. InSAR results validation with GNSS (Tenerife island).

1. VALIDATION PROCEDURE FOR THE VOLTERRA AREA

The Volterra test-site for SAFETY covers the whole municipal territory of Volterra in Tuscany Region, Italy. Within the test site, the main urban areas are the historic town of Volterra, located at the centre of the study area, and Saline di Volterra town in the SW portion of the area. Regarding the road network, the main roads are the Regional Road SR68 that crosses the municipality with NW-SW direction, connecting Volterra and Saline di Volterra towns, and the County Road SP15 from Volterra city center towards N. Another minor but relevant road is the SR439dir that runs near the SP15 with NE direction.

The above-mentioned road paths are somewhere tortuous and prone to ground movements as they run throughout clayey and landsliding terrains. Furthermore, from the point of view of mobility, these roads are very strategic because represent the main transportation corridors between the localities of the municipality. Thus a stability analysis of the whole surrounding territory is required for Civil Protection purposes. For SAFETY, we analyze the geo-hazard susceptibility map of the Volterra area (Task E, Action E.2) by means of a method exploited within LAMPRE project and then we are going to validate it according to already tested statistical procedures (Catani et al., 2013; Guzzetti et al. 2005, 2006; Rossi et al., 2010).

Moreover, we are going to validate the geo-hazard activity maps (Task E, Action E.3) produced for the Volterra municipality throughout the procedure already proposed and employed in the DORIS project and reported in Bianchini et al. (2013). The procedure aimed at evaluating the “confidence degree” of the product activity maps. This approach will be used and improved within SAFETY by exploiting available external independent sources, such as damages inventories, in situ measurements, field checks for validating the produced maps. The geo-hazard activity map related to SAR data could be additionally validated and compared with the PSI Hotspot and Clustering Analysis (PSI-HCA) method, relying on the procedure proposed by Lu et al. (2012).

All the proposed validation methodologies aim to validate SAFETY results and to provide reliable tools that would contribute to future slope instability hazard/risk evaluation, in order to address preventive and corrective measures on the urban fabric and along the road-network of the municipality.

1.1 Geo-hazard susceptibility map in the Volterra municipality

The geo-hazard susceptibility map in the Volterra municipality produced with the software developed in LAMPRE project (LSMMs tool, which exploits different methods of multivariate statistical classification, i.e. Linear discriminant analysis model, Quadratic linear discriminant analysis model, Logistic regression model, and Self-optimizing neural network model) will be validated in SAFETY by evaluating the quality of the susceptibility zonation.

The validation will be performed through comparison with landslide inventories and through production of plots showing True Positive (TP), True Negatives (TN), False Positives (FP) and False Negatives (FN) for correct prediction of landslide occurrences.

In particular, the LSMMs software will produce the landslide susceptibility model (Fig. 1-1 A) and the associated uncertainty map showing a preliminary zonation of the quality of the susceptibility product map (Fig. 1-1 B).

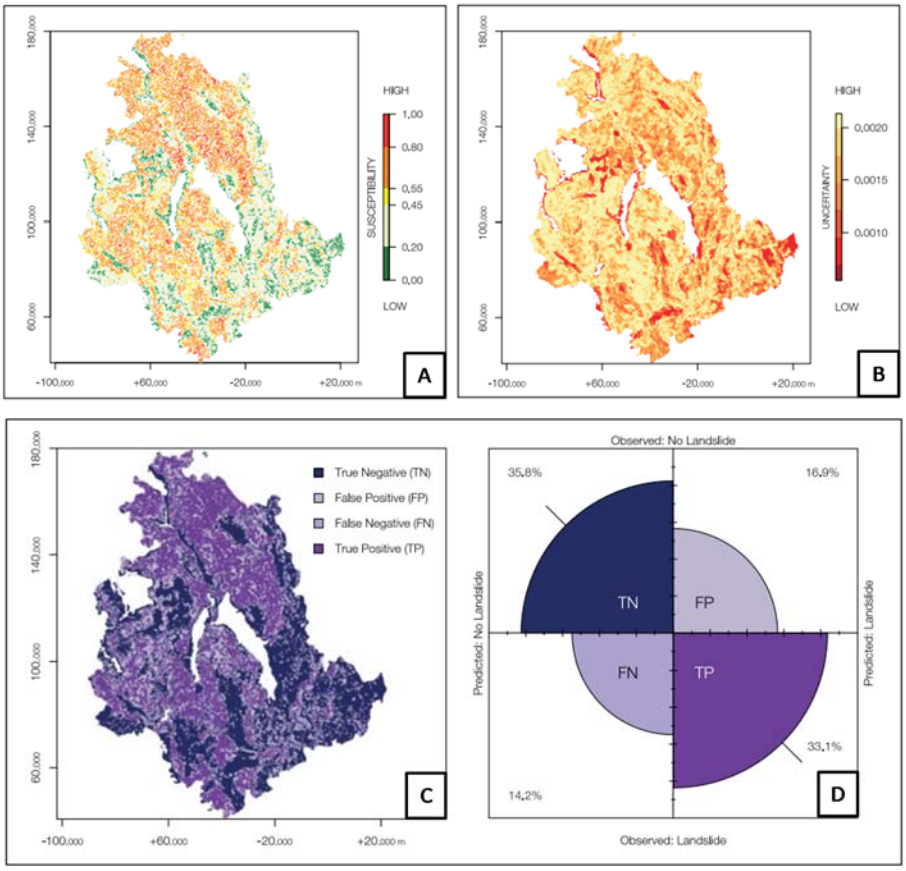

Figure 1-1. Map and validation products with LSMMs Tool (Rossi et al., 2010): (A) Landslide susceptibility map for the Umbria region, created within the LAMPRE project; (B) Uncertainty in the landslide susceptibility classification map; (C) Areas classified correctly and incorrectly in the landslide susceptibility map; (D) Fourfold plot showing the proportions of areas classified correctly and incorrectly (True positive, True Negatives, False positives and False negatives).

Other measures of the quality of the susceptibility model are shown in Figure 1C revealing the geographical location of the areas identified correctly and incorrectly as landslides using the susceptibility model. The four-fold plot shows the proportion of the territory that was classified correctly and incorrectly as landslide prone or landslide free (TP, TN, FP, FN). In the plot, correct predictions are: True Positives (TP) where landslides were predicted in the model and observed in reality, and True Negatives (TN) where landslides were neither predicted nor observed. False positives (FP) show the proportion of the area predicted as landslide prone where no landslides were observed, and False Negatives (FN) show areas where no landslides were predicted in the model but were effectively observed in reality.

A further step for validating outputs of the proposed method consists in the use of the empiric ROC (Receiver Operating Characteristics) area analysis (Frattini et al. 2010). According to the ROC analysis, the Area under Curve (AUC) value related to both success- and prediction-rate curves is computed to examine the precision of the method. The AUC value is usually used when a general measure of predictive capacity is desired and it ranges from 0.5, indicating an inaccurate model with random fit, up to 1.0 for an ideal model with a perfect fit (Fig. 1-2).

The bivariate statistical analysis widely used in scientific literature for evaluating landslide susceptibility (e.g. Yin and Yan 1988; Van Westen 1997; Lee et al. 2006; Magliulo et al. 2008; Yalcin 2008) could be applied in order to compare and test results. This approach, in particular the Information Value Method, was already used on the Volterra area to evaluate the badland susceptibility in the study area in a GIS (Geographic Information System) environment, showed in Bianchini et al. (2016), and could be applied also to landslide phenomena prediction (Fig. 1-3), considering different suitable parameters.

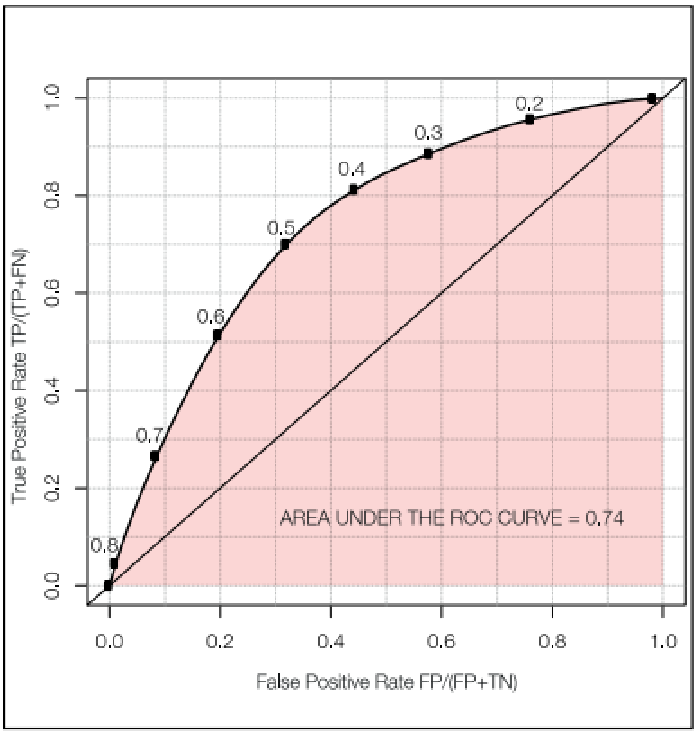

Figure 1-2. Receiver Operating Characteristic (ROC) plot for the landslide susceptibility model.

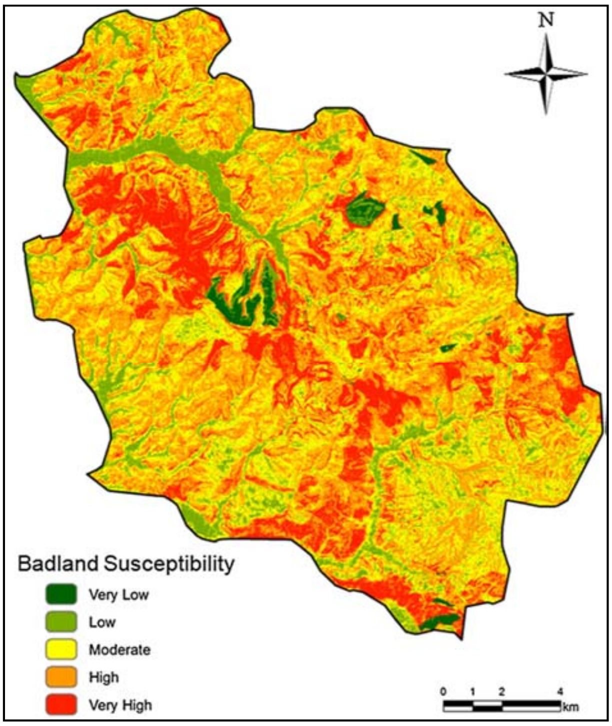

Figure 1-3. Badland susceptibility map of the Volterra municipality (Bianchini et al., 2016).

A Receiver Operating Characteristic (ROC) plot can be also used after the application of Information Value method, in order to evaluate quantitatively the performance of the landslide susceptibility zonation. In the ROC plot, the larger the area under the curve, the better the susceptibility model and the associated terrain zonation. The resulting graph includes a prediction rate curve'' and a "success rate curve" (Fig. 1-4).

The ''prediction rate curve'' shown in Fig. 1-4 was the one derived for badland susceptibility map in Volterra area and was created by using known badland areas of the ''validation set'' set, that was not used for the susceptibility map generation. The prediction rate curve shows the badland ''validation set'' on the y-axis, represented as cumulative percentage of the relative frequency, and the areas included in the susceptibility levels (ordered from the higher class to the lowest one) on the x-axis, represented as relative frequency in cumulative percentage. The ''success rate curve'' was produced by plotting the cumulative percentages of the badland areas of the ''training set'' on the y-axis, and the cumulative percentages of susceptibility areas on the x-axis, arranged from the highest to the lowest susceptibility value (Fig. 1-4). This curve allows testing the reliability of the method used to obtain weights and susceptibility map.

1.2 Geo-hazard activity map on the main road SR68 and county road SP15 in the Volterra municipality

The geo-hazard activity map produced in Task E Action E.3 will be also validated by means of the method proposed by Bianchini et al. (2013).

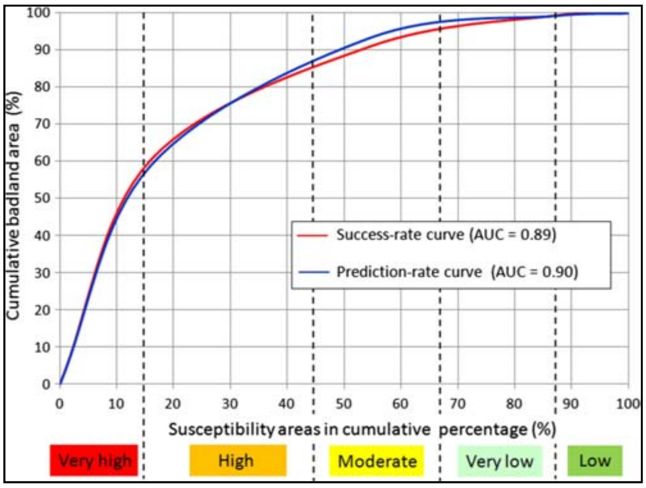

Figure 1-4. Success rate and prediction rate curves that represent, respectively, the effectiveness of the used method and its predictive power (Bianchini et al., 2016).

The confidence degree of the SAR data-based product-map, i.e. the geo-hazard activity map, can be assessed in order to determine how truthful and reliable it is, on the basis of the availability and use of radar data and of other external information sources. Thus, the confidence degree of the map is evaluated throughout its comparison with external data, such as damages inventories, landslide inventory map (LIM), point-like landslide events databases, in situ measurements and field checks.

Bianchini et al. (2013) proposed the confidence degree evaluation of “Landslide and Ground motion Activity Maps”, where the “activity map” is intended as a spatial distribution of potentially active areas characterized by high ground motion rate. This evaluation aims at assessing if the measured displacement represents landslides dynamics. It is important to highlight that the reliability on the PSI SAR measurement itself is not evaluated, but whether this measurement is related to landslide activity or not. Three confidence degree levels are established - low, medium and high – depending upon ground truth data availability (Fig. 1-5).

By comparing LIM, SAR ground motion data and ground truth data, we can assess on one hand “True Negatives” (i.e., inactive landslide producing damages), and “True Positive” (i.e., active landslide producing damages) and on the other hand, “False Positives” (i.e., active landslides not producing damages), and “False Negatives” (i.e., inactive landslides not producing damages) (Bianchini et al., 2013) (Fig. 1-6).

A high confidence degree is attributed to landslides that can be assessed as “True Positive” or “False Negative” phenomena, as measured displacements (active/inactive) can be correlated with reported damages (occurred/not occurred) (Fig. 1-6).

	Geo-thematic data		
Confidence degree	Low	Medium	High
Landslide and Ground motion activity map	No sufficent PS data No LIM (Outpoints)	PS data and no Ground truth	PS data and Ground truth

Figure 1-5. Confidence degree determination for landslide and ground motion activity maps.

In the Volterra test site, available ground-truth data include different types of external information:

- *in situ* measures from inclinometers located in the SW portion of the Volterra urban area, provided by GEOPROGETTI and GEOSER companies (GEOPROGETTI, 2010);
- a database of real cases of events and damages to structures and roads occurred in the spanning time 2010-2016 (Fig. 1-7), with particular attention to the urban areas (Volterra and Saline di Volterra) and to the roads SP15, SR68 and SR439dir.
- Field checks and survey campaigns carried out by DST-UNIFI during years 2014-2016, after the emergency stage linked to the wall collapses occurred in winter 2014 up to nowadays, with particular attention to the urban areas (Volterra and Saline di Volterra) and to the road network, which are the most relevant elements at risk with high exposure in the area of interest.

Additionally, the geo-hazard activity map related to SAR PSI (Persistent Scatterer Interferometry) data could be validated and compared with a PSI Hotspot and Clustering Analysis (PSI-HCA) method, relying on the procedure proposed by Lu et al. (2012, 2014).

The spatial statistics approach of PSI-HCA aims to obtain a continuous estimation of PS distribution from their spatially correlated velocities. PSI-HCA is composed of two spatial statistic approaches: (a) Getis-Ord Gi* statistics (Getis and Ord, 1992) calculated for each single PSI point target and (b) kernel density estimation (Silverman 1986), derived based on calculated Gi* values.

The output of PSI-HCA is a PS hotspot map represented by the kernel density values. PSI-HCA can be performed on both ascending and descending PS datasets, separately. Figure 1-8 shows application of the PS hotspot map in the Arno River basin in Lu et al. (2014). Pixels with positive kernel density values are displayed with blue colours whereas pixels with negative kernel density values are rendered on red colours. Both blue and red hotspots indicate where potential mass movements exist, with deeper colour indicating higher clustering level of high velocity PS, and thus can be an indicator of possible landslide occurrence useful to validate the spatial geohazard maps of the test area.

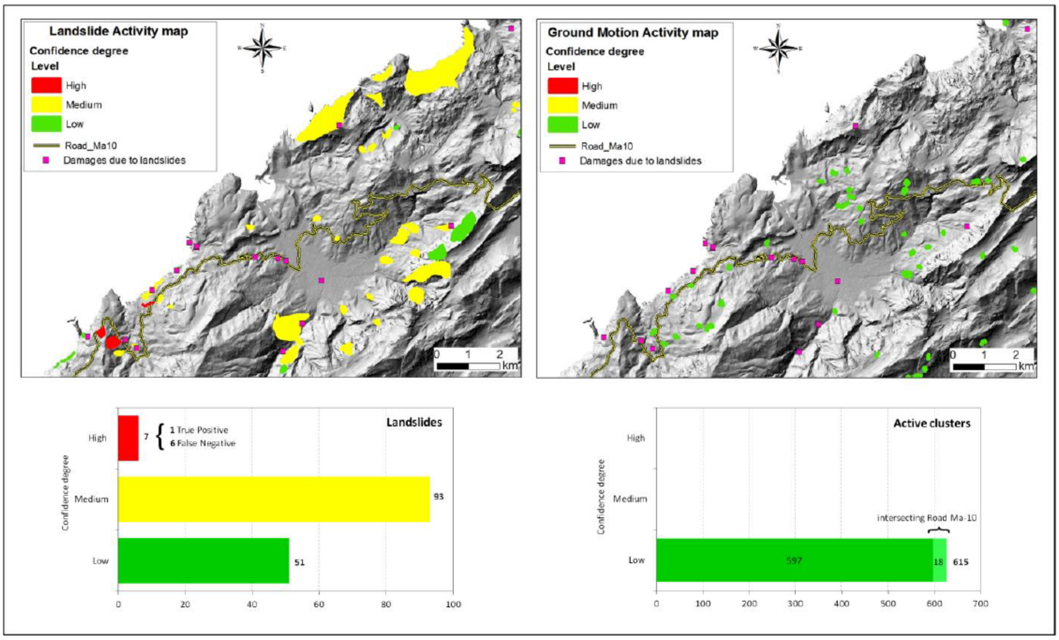

Figure 1-6. Confidence degree evaluation of Activity maps on the Tramuntana Range (Mallorca, Spain) in Bianchini et al. (2013).

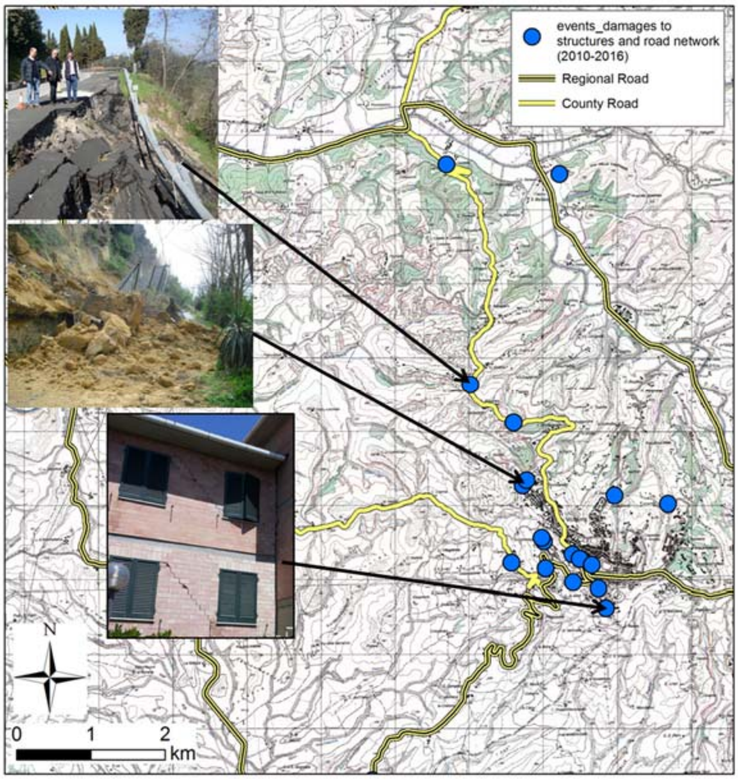

Figure 1-7. Example of the events and damages database on the Volterra test site.

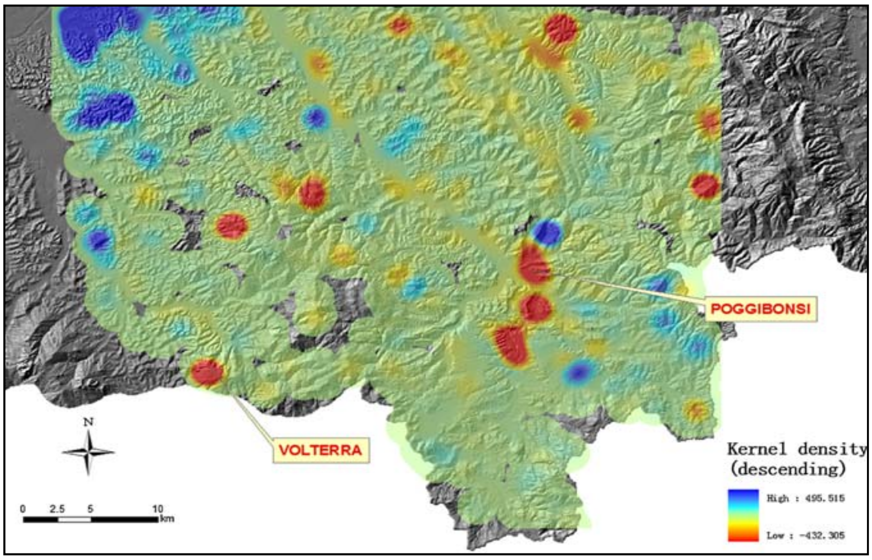

Figure 1-8. The landslide hotspot map covering the area between Volterra and Poggibonsi in the Arno River basin in Lu et al., (2014): a hotspot map derived from a kernel density estimation using ascending using descending RADARSAT PS: red hotspots correspond to PS moving downwards and/or westwards, whereas blue hotspots correspond to PS moving upwards and/or eastwards.

2. VALIDATION PROCEDURE FOR THE CANARY ISLANDS

2.1 Rockfall hazard along the GC-200 road (West Gran Canaria)

The test-site selected for SAFETY is located in the western extreme of Gran Canaria, between the localities of Agaete and Aldea, along the GC-200 road, the main transportation corridor between the two localities. The road path has a length of 34 km, and it is very tortuous following the contour of the coast, a very step coastline. In fact, the GC-200 is one of the most hazardous roads in south-Europe, as it runs throughout the highest cliffs in Europe (Risco Faneque, 1027 m a.s.l.). From the point of view of mobility, the GC-200 is a strategic road on the island and Civil Protection of the Canary Islands requires a detailed analysis of the rockfall hazard along the road, as numerous rockfalls affect and even interrupt the road every year. A moderate seismic activity characterizes the region. During the volcanic crisis that affected the El Hierro Island between 2011 and 2013, thousands of earthquakes were registered with magnitudes of up to 5.1 Mw. In 2004, numerous earthquakes were also registered close to the island of Tenerife, causing a great social alarm over the possible reactivation of El Teide volcano.

In SAFETY will be applied the same procedure previously tested in the Tramuntana range of Mallorca (Spain) along the Ma-10 road, in the framework of the LAMPRE Project (Mateos et al., 2015). The main goal will be to calibrate and validate rockfall modelling using STONE (Guzzetti et al. 2002). STONE is a physically-based rockfall simulation computer program which computes 2D-3D rockfall trajectories. The script requires, among other inputs, maps of the dynamic rolling friction and of the normal and tangential energy restitution coefficients that depends directly on the geology of the region. Taking into account the instrumental seismicity recorded in the Canary Islands (IGN), two seismic scenarios will be contemplated and considered in the rockfall simulations.

STONE outputs can be part of a methodology focused to evaluate rockfall hazard and risk and to address preventive and corrective measures along the GC-200 road.

2.1.1 Methodology

To validate the STONE modeling along the GC-200, two main stages will be carried out: calibration and validation.

Calibration

To calibrate the friction and energy restitution coefficients, which are required for the modelling, we'll select a number of well-known rockfalls that occurred in the study area, where several different lithologies outcrop. In a first step, values of friction, normal and tangential restitution coefficients for STONE will be obtained from the literature (Guzzetti et al. 2003; Guzzetti et al. 2004). Then, for single well known rockfall, the map of the trajectories count will be compared with the real extent of the rockfall deposits mapped in the field and by ortophotos. The process will be repeated for several single rockfall events, changing the parameters until results are judged satisfactory (the extent and shape of the simulation matching the field mapping, see Fig. 2-1). Best results will be summarized computing average statistical values (mean, median and mode) for each parameter and for each geotechnical unit. In a second step, a statistical analysis will be carried out to decide the most appropriate average values that will be considered as the calibrated parameters.

To accomplish the calibration step, we need to prepare/obtain the following inputs:

- A geotechnical map for the study area will be prepared, considering the geological map from IGME (GEODE, www.igme.es) at 1.25.000 scale and the guideline of the geotechnical map provided by IDE-Canarias. The geotechnical classification will include all the lithologies outcropping in the area. We roughly propose five categories:

    - o Hard rocks
    - o Moderately hard rocks
    - o Soft rocks
    - o Soft soils
    - o Very soft soils

- A detailed map of all rockfall, including source areas, prepared using aerial photos and field surveys.

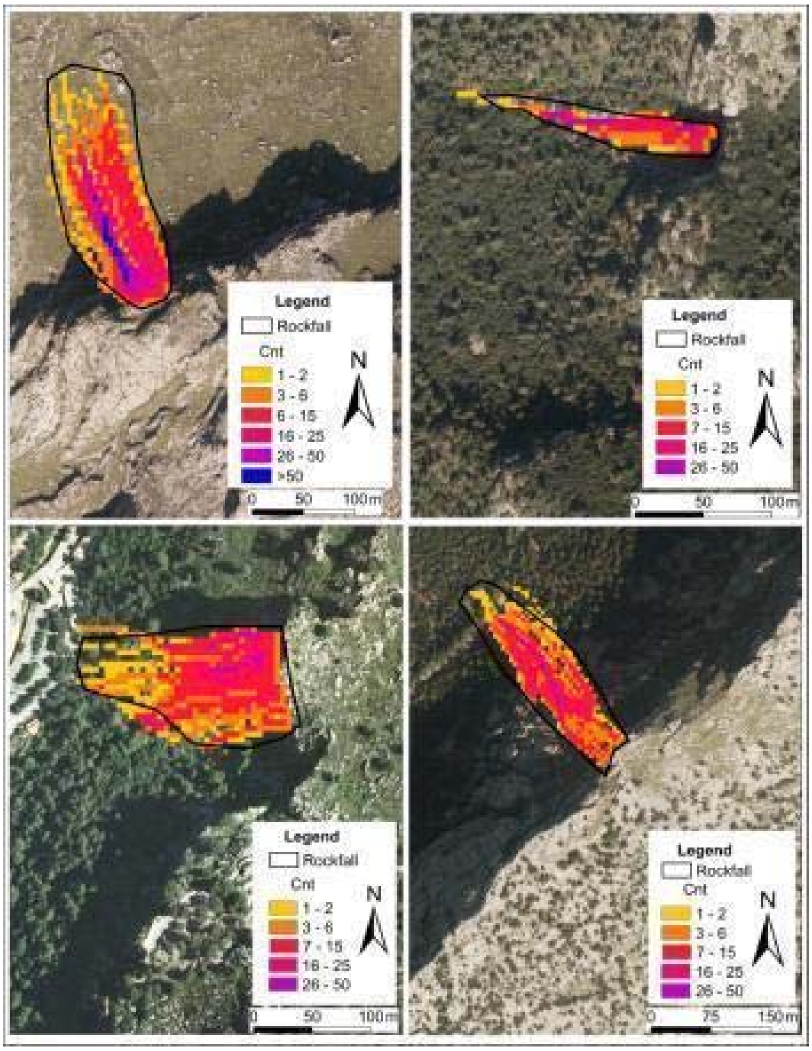

Figure 2-1. Four cases exploited for STONE calibration in the Tramuntana range of Mallorca. Output values correspond to the cumulative count of rockfall trajectories (colors). The real area covered by the rockfall boulders is delimited by the polygon with black boundary. The figures show the best simulation for each case obtained after numerous attempts (Mateos et al., 2015).

Validation

The validation of the calibrated parameters, will be performed in two phases:

- In the first phase, 10 rockfalls with a higher magnitude in the test-site will be selected and will be modelled using STONE with the calibrated parameters. Results will be validated by applying two confidence tests. The first (Fig.2-2) is based on the comparison between the mapped and the simulated rockfall, analyzing the histograms which show the number of cells falling inside and outside the mapped extent of the failure (Guzzetti et al. 2003). The second is a new approach (Mateos et al., 2015), which considers not only the number of cells inside the rockfall deposit (success), but also the number of cells inside the real deposit and with no modelling results (failures).
- In the second phase, a final validation will be carried out along the GC-200 road, considering the complete inventory of rockfalls that affected the road. STONE simulations will run with the calibrated parameters considering all possible source areas along both sides of the road. Results will be compared with the real cases to determine the accuracy of the simulation.

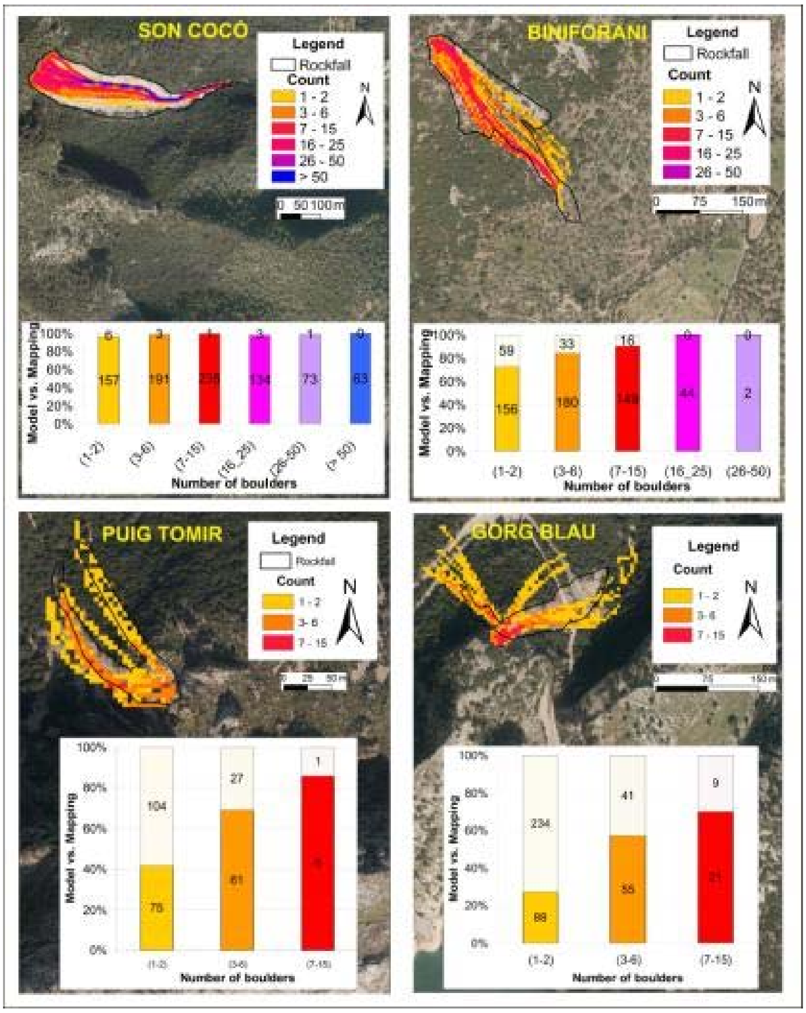

Figure 2-2. One of the validation tests applied in Mateos et al., (2015). In the maps are shown the comparison between the extent of the mapped rockfalls (black polygon) and the simulated trajectories (colors). Histograms show the number of cells falling inside (colored) and outside (white) the mapped rockfall.

The validation procedure, requires the following inputs:

- A detailed mapping of the 10 rockfalls selected for the first phase. This will be performed by means of aerial photos and field survey.
- Identification of the all the potential source areas along the road. This will be accomplished considering the slope angle obtained from topographic maps (1:5.000 scale; IGN 2006) combined with aerial photographs (1:18.000 scale) and field works.
- Update of the rockfall inventory along the GC-200 road.

Rockfall simulations considering seismicity

After the calibration and validation of STONE modelling, in the test-site, new simulations can be carried out considering two different seismic scenarios:

- The first will be similar to the event that occurred on 9th May 1989, when the earthquake of highest magnitude ever recorded (5.2 Mw) occurred in the surroundings of Gran Canaria. Based on this earthquake data we will calculate the starting velocity (input) for the STONE simulation.

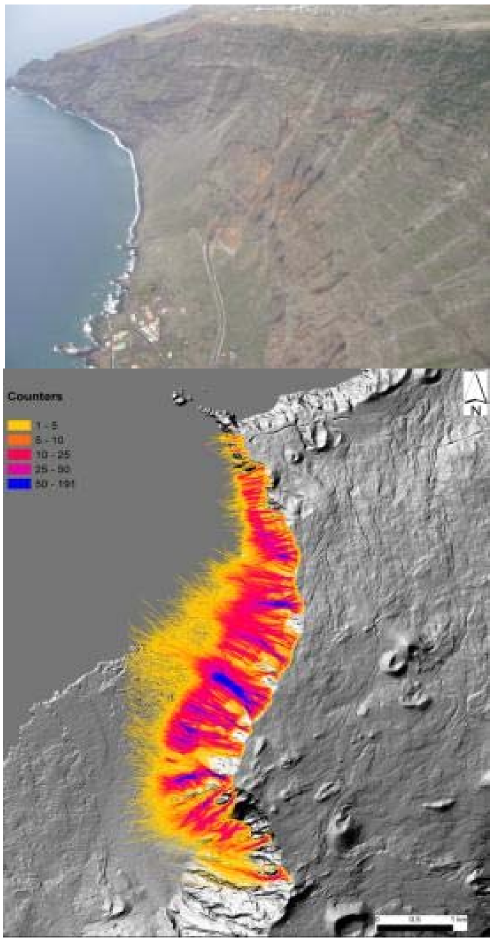

Figure 2-3. STONE modelling carried out in El Hierro (along the HI5 road, Frontera) that consider the real seismic scenario that occurred during the volcanic crisis in 2011 (earthquake of 4.4 Mw). (IGME, 2011).

- The second will consider the highest magnitude-earthquake recorded during the El Hierro volcanic crisis (5.1 Mw), that occurred on 27^{th} December 2013, close to the northern coast of the island of El Hierro. Based on this earthquake data, we will calculate the starting velocity (input) for the STONE simulation. IGME in October 2011 ran STONE along the HI5 road, located in the northern part of El Hierro (Frontera) during the first volcanic crisis. Fig. 2-3 shows the IGME (2011) results taking into account an earthquake of 4.4 Mw (18 November 2011) with the epicenter very close to Frontera.

Discussion

Finally, results will be discussed with the technical team from the Road Maintenance Service of Gran Canaria as well as with the Civil Protection team, with the aim to lay down new guidelines for the GC-200 road prevention and prediction measures.

2.2 InSAR validation with GNSS in the Canary Islands

The test site selected for the validation is Tenerife (Canary Islands). Tenerife is the largest island of the archipelago, with a surface of 2.057 km^2, and also the most populated one. The highest point of the island, Mount Teide is the third largest volcano in the world from its base at the bottom of the sea which has showed polygenetic volcanism. It was identified by IAVCEI as being worthy of particular study in light of its history of large, destructive eruptions and proximity to populated areas.

Apart from the Teide stratovolcano, two rift zones run NW-SE and ENE-WSW directions and are marked by parallel rows of aligned cones and eruptive fissures (e.g. Ancochea et al. 1990, Carracedo 1994, Carracedo 1996, Martí et al. 1996) and fault/dyke swarms (e.g. Walter and Schmincke, 2002, Walter et al. 2005). In the southern part of the island basaltic volcanism is characterized by scattered vents and non-coherently orientated eruptive fissures. It has been associated with a third rift zone orientated N-S which, with the other ones, may comprise a three-armed rift structure (e.g Carracedo 1994, Carracedo 1996, Walter and Troll 2003). Rifts show monogenetic volcanism usually of basaltic composition. Main concern about potential future volcanic activity has been addressed towards basaltic eruptions taking place the rift zones, as they have occurred in historical times, however the probability of having a new eruptions of Teide is not negligible (Martí et al. 2012).

After volcanic unrest episode in 2004 at Tenerife Island, IGN was commanded by law to hold responsibilities on volcanic monitoring management in Spain, communication and determination of associated risks. According to this aim, a multi-parametric network of stations was deployed and maintain in the Canary Islands.

Deformation is one of the main precursors of a volcanic eruption. Currently IGN operates a network of 18 GNSS stations, supported by data collected from other public networks, as IGS and GRAFCAN GNSS permanent ones.

In Tenerife, IGN network is comprised of eight stations uniformly distributed along the island. Since 2007, GNSS time series have been generated and analyzed daily. This procedure has allowed us to study background movements of some GNSS stations and seasonal effects. It was also able to detect the volcanic unrest on El Hierro Island in 2011, which ended in a submarine eruption, and the 2012-2014 post-eruption volcanic activity (López C. et al., 2012; Klügel et al., 2015).

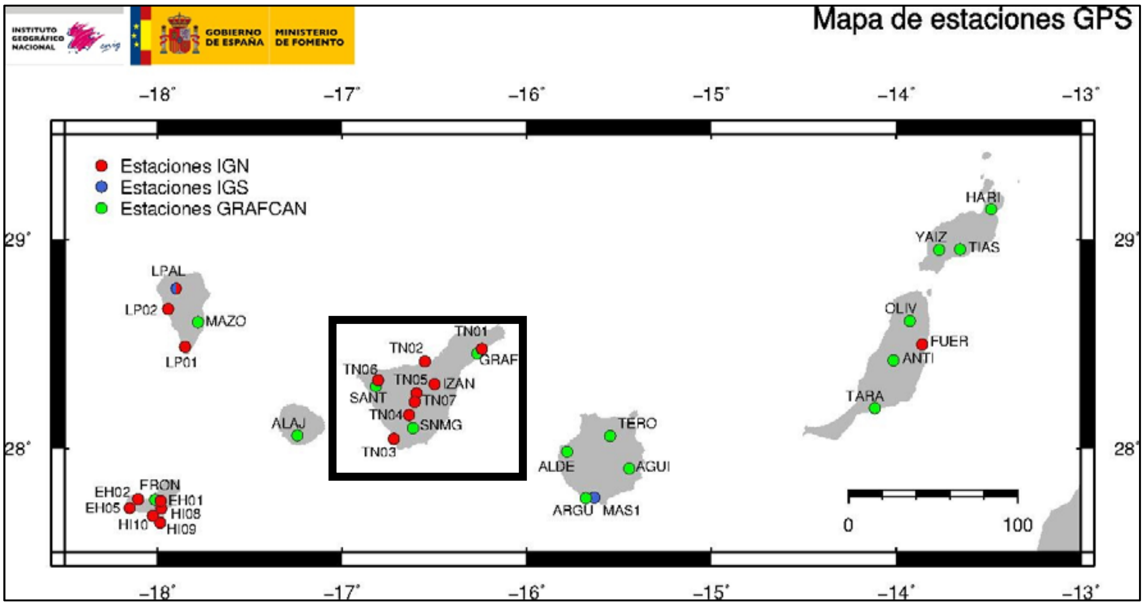

Figure 2-4: GNSS permanent networks in Canary Islands.

We aim here is to describe the criteria adopted to validate the Deformation Activity Map, the SAFETY product created with Sentinel-1 images and included in deliverable C2, using time series analyses from the IGN-GNSS networks. Final and daily NEU (north, east, up) coordinates with tectonic plate movement removed, will be used for the validation. For further details on GNSS processing approach for volcano monitoring see García-Cañada et al., 2013.

2.2.1 Validation procedure

GNSS time series

1. **GNSS-NEU time series:** Generation of GNSS-NEU time series for the selected time interval and estimation of velocities by linear regression.
2. **GNSS-NEU time series projection to LOS**: To be able to compare InSAR and GNSS time series, GNSS-NEU time series need to be projected into the line-of-sight (LOS) direction (Hanssen, 2001):

$$d_r = d_u \cos(\theta_{inc}) - \sin(\theta_{inc}) \left[d_n \cos\left(\alpha_h - \frac{3\pi}{2}\right) + d_e \right]$$

According to the Sentinel-1 descending orbits used in this analysis, these parameters are:

- d_r : deformation vector in LOS direction,
- d_n, d_e, d_u: deformation vectors in north, east and up directions coming from GNSS-NEU time series,
- θ_{inc} : incidence angle for the area of interest (between 36º47 and 41º85, depending on the island),
- α_h : orbit heading (~192.5º).

3. **Velocity estimation of the GNSS-LOS time series**: According to the observed trends at GNSS-NEU time series, we decide to use a common least squares approach to estimate velocities for the projected time series.
4. **Interpretation of GNSS-LOS deformations**: According to projected time series and estimated velocities, we perform a first interpretation of the results. Accumulated deformation above 5 mm accompanied by a defined trend is considered an active GNSS-LOS candidate. On the other hand, deformations below 5 mm of accumulated deformation, with or without trend, are stable GNSS-LOS candidates.

InSAR time series

5. **Area selection around GNSS station**: According to persistent scatters (PS) deviation (10 mm), instead of selecting the time series of the closer PS to the GNSS station, we decide to select an area of a certain size around the GNSS station and study the behavior of the PS included on it.
   An equal-size-area or an equal-number-of-pixel criterion can be used to choose the area size. In both cases, a significant number of pixels are mandatory to obtain a representative behavior of the area.

   We perform some tests to find a suitable radius for the area, always larger than the PS size, 40 m x 40 m after multi-looking. In this case, we finally decided to use an equal-area criterion of 350 m radius around each GNSS station.
6. **Analysis of the PS behavior and final area selection:** Time series for every PS inside selected areas around GNSS stations are generated and analyzed. Two situations can occur:
   a. PS in the area show the same behavior: area is well selected and we can proceed to calculate an average to work with. We also estimate velocities using same approach used in the GNSS time series generation (3).
   b. PS in the area show different behavior: the area needs to be reduced until we observe all the PS have the same behavior (a).

   In case we carry on observing the different PS behaviors despite successive area reductions, it is very likely that the location is noisy and the validation could not be carry out so we possibly have to discard the GNSS site and study the causes.
7. **Interpretation of InSAR deformations:** According to the averaged deformations obtained, we perform a first interpretation of the results. Accumulated deformation above 10 mm accompanied by a defined trend is considered an active InSAR candidate. On the other hand, accumulated deformations below 10 mm, with or without trend, are considered stable InSAR candidate.

Validation

8. **Validation of InSAR with GNSS-LOS time series:** according to criteria established in (4) and (7), we compare both time series. The following situations can take place (Table 2):

Cases	A. InSAR deformation	B. InSAR no deformation
A. GNSS-LOS deformation	**AA. VALIDATED**	**AB. NO VALIDATED**
B. GNSS-LOS no deformation	**BA. NO VALIDATED**	**BB. VALIDATED**

Table 2-1: Validation cases

- **Case AA**: Significant deformations are observed in both GNSS-LOS and InSAR time series. Acceptable differences between both in magnitude and velocity can take place attending to different noises of the time series.
- **Case AB**:

  Possible causes:
  - o If accumulated deformation is around 5mm, deformation could be detected in the GNSS-LOS time-series but not in the InSAR time series as being the latter generally noisier. GNSS-LOS deformation is punctual and selected PS included in the 350 meters area around the station do not represent the real movement of the station.
  - o GNSS-LOS deformation is punctual and selected PS included in the 350 meters area around the station do not represent the real movement of the station.
- **Case BA**

  Possible causes:
  - o As GNSS measures punctual deformations it is possible that the station itself is not suffering movements but the 350 meter radius area around it does.
- **Case BB**: No significant deformation is observed in GNSS-LOS or InSAR time series, regardless of the noise of the series (Fig. 2-5).

In case the validation is still unclear we can make use of IGN-GNSS complete time series generated since 2007, external information (as land use map, rockfall inventory map, element at risk catalogue and damage events database) and field campaigns.

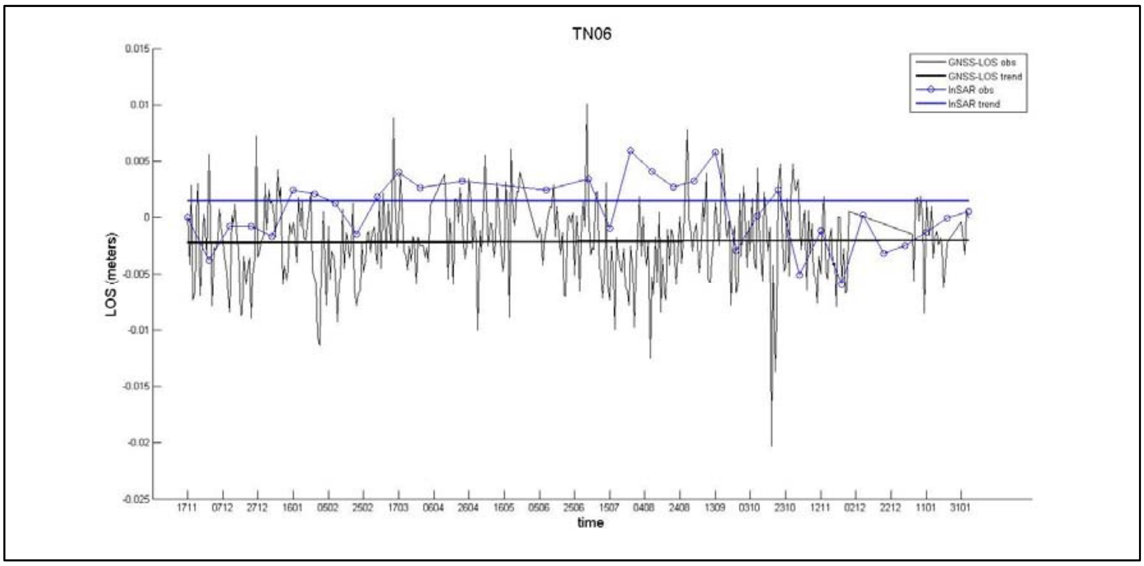

Figure 2-5: Example of case BB for station TN06 (Tenerife).

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