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PhD Thesis

**Real Time GNSS for the study of
geohazards through data mining and
modelling processes**

By

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1. Introduction.....	1
1.1 Landslides	4
1.2 Deep-Seated Gravitational Slope Deformations (DSGSDs) ...	24
1.3 Monitoring Techniques	31
<i>1.3.1 Engineering-geological monitoring</i>	<i>33</i>
<i>1.3.2 Remote Sensing Techniques</i>	<i>42</i>
<i>1.3.3 Topographic and geodetic techniques.....</i>	<i>52</i>
2. Data Processing Methodology.....	82
2.1 GNSS Data Analysis	82
2.2 SAR Data Analysis.....	90
3. Case Studies.....	93
3.1 Fiastra DSGSD	93
3.2 Cuenca landslide	99
4. Results	106
4.1 Fiastra DSGSD.....	106
4.2 Cuenca landslide	115
5. Discussion	125
6. Conclusions.....	130
References	133

1. Introduction

The monitoring of geological phenomena is a fundamental aspect for understanding instability processes and for managing the related risks. Landslides, subsidence, and slow ground deformations represent complex events, influenced by multiple natural and anthropogenic factors, whose evolution can cause severe damage to infrastructure and local communities. For this reason, the definition of reliable interpretative models and the development of mitigation strategies cannot disregard the adoption of advanced monitoring techniques capable of providing accurate and continuous data on both superficial and deep-seated displacements.

Monitoring techniques can be classified into conventional geotechnical and geodetic methods and innovative methods based on satellite remote sensing and space geodesy. In recent decades, in particular, Global Navigation Satellite Systems (GNSS) and Synthetic Aperture Radar Interferometry (InSAR) have played a central role in the study of ground deformations, thanks to their high accuracy and the possibility of multitemporal and multiscale investigation.

GNSS monitoring enables the determination of absolute three-dimensional coordinates with millimetric accuracy, making it possible to detect very slow displacements and to reconstruct both horizontal and vertical components of movements. This approach can rely on permanent station networks, ensuring continuous and real-time acquisition, or on periodic survey campaigns, which allow for point-wise but more cost-effective control. The main limitations are related to the punctual nature of observations, constrained by the number and distribution of receivers, and the need to interpolate data to reconstruct displacement fields at a larger scale.

On the other hand, SAR interferometry (InSAR) provides wide-area deformation maps, with spatial resolutions on the order of meters and sensitivity to millimetric displacements along the satellite's Line of Sight. Differential InSAR (DInSAR) and Persistent Scatterer Interferometry (PSI) techniques have

proven highly effective in monitoring slow-moving landslides, subsidence, and deformations induced by anthropogenic activities. Nevertheless, these measurements are relative, one-dimensional, and subject to limitations due to temporal decorrelation, vegetation cover, or slope geometry.

To overcome the intrinsic limitations of individual methodologies, numerous studies have highlighted the advantages of an integrated GNSS–InSAR approach, which combines the absolute, three-dimensional precision of GNSS measurements with the spatial coverage and high density of interferometric data. Such synergy provides more reliable and comprehensive information on the dynamics of the phenomena, improving the ability to identify precursors of instability and to develop predictive models supporting land management and civil protection.

The aim of this research is to investigate the capability of GNSS data as an effective geodetic monitoring tool for the analysis of geological phenomena, with particular focus on slope deformation processes. To overcome the intrinsic limitations of the individual methodologies, an integrated GNSS–InSAR approach was applied, combining the three-dimensional precision of GNSS measurements with the wide spatial coverage and high information density provided by interferometric data. This synergy enables the acquisition of more reliable and comprehensive information on the dynamics of deformation processes, improving the ability to identify precursors of instability and to develop predictive models supporting land management and civil protection.

The proposed approach was tested on two representative case studies: the Deep-Seated Gravitational Slope Deformation (DSGSD) of Fiastra, Italy, and the landslide affecting the city of Cuenca, Ecuador. In the first case, the integration of GPS and DInSAR data allowed for a detailed characterization of deep-seated gravitational processes and highlighted the role of seismic factors in the reactivation and reorganization of slope movements.

In the second case, the combined analysis of GNSS and SAR data enabled the reconstruction of the three-dimensional kinematics of the landslide, the

identification of areas exhibiting different deformation behaviors, and the validation of the reliability of the GNSS monitoring network as a diagnostic and early-warning tool.

Finally, this research led to the development and testing of a real-time permanent GNSS network capable of automatically generating displacement time series and issuing alerts when predefined movement thresholds are exceeded. This innovation represents a significant step toward the implementation of effective and sustainable early warning systems, demonstrating the potential of GNSS data, integrated with interferometric information, for the prediction and mitigation of landslide hazards.

To provide a clear understanding of the research framework and methodological development, the structure of this thesis is organized as follows:

- Chapter 1 provides an overview of landslide phenomena, including their factors, causes, nomenclature, and classification systems, with particular emphasis on the Varnes classification. It also introduces Deep-Seated Gravitational Slope Deformations (DSGSD) and reviews the main monitoring techniques, encompassing engineering-geological methods, remote sensing approaches (photogrammetry, LiDAR, SAR), and topographic and geodetic techniques, including GNSS-based solutions.
- Chapter 2 illustrates the data processing methodology, detailing the procedures adopted for GNSS and SAR data analysis.
- Chapter 3 presents the case studies, namely the Fiastra DSGSD and the Cuenca landslide, describing their geological settings and monitoring infrastructure.
- Chapter 4 reports the results of the geodetic and interferometric analyses carried out for the two case studies.
- Chapter 5 discusses the implications of the obtained results in the context of landslide monitoring and interpretation.
- Chapter 6 summarizes the conclusions and provides recommendations for future research and landslide risk management.

1.1 Landslides

Landslides represent one of the most destructive natural phenomena worldwide. They occur in heterogeneous environmental contexts and cause losses in terms of population, resources, and infrastructure, with economic consequences that are often difficult to quantify, particularly with regard to indirect damages.

Because of the significant impact that landslides exert on the territory and the numerous related issues, several scholars have proposed different definitions of the phenomenon over time (Terzaghi, 1950; Varnes, 1958a; Bates & Jackson, 1987). Among the most notable is the definition provided by Varnes (1978), who stated that “*landslides are gravity-controlled movements, either shallow or deep, rapid or slow, of the materials forming a slope or an entire landform*”. Later, Cruden (1991) defined a landslide as the movement of a “*mass of rock, earth, or debris down a slope*”.

Factors and causes of landslide phenomena

Landslides can have multiple predisposing or preparatory causes, but typically only one triggering cause (Wieczorek, 1996). These causes may be:

Intrinsic causes: related to the nature of the slope material, which may be weak, sensitive, altered, fractured, characterized by unfavourably oriented discontinuities, or affected by permeability contrasts.

Geomorphological causes: associated with tectonic or volcanic uplift, erosion, or deposition at the crest or along the slope.

Physical causes: including intense rainfall, earthquakes, volcanic eruptions, frost weathering, wetting–drying cycles.

Anthropogenic causes: related to slope foot excavations or crest loading, agricultural activities, deforestation, mining, and the accumulation of waste or debris.

Overall, landslide causes are generally classified as:

1. structural or predisposing, when linked to geological, morphological, or hydrogeological factors.

2. occasional or triggering, when associated with climatic, vegetational, or anthropogenic factors, as well as with seismic or volcanic events.

A landslide occurs when, along a surface or shear band within the slope, the mobilized shear stresses (demand, D) equal the shear strength capacity (C) of the material:

$$FS = C/D \leq 1$$

The demand D depends on slope geometry (inclination, extent) and loading conditions (e.g., constructions, seismic actions), while the capacity C is controlled by the mobilized shear strength along the sliding surface, which varies according to deformation (stress–strain behavior) and pore water pressure (groundwater table position). A slope initially stable ($FS > 1$) may become unstable due to:

- increase in D , caused by additional loading (e.g., construction, seismic event) or enhanced slope activity (e.g., erosion or undercutting);
- reduction in C , due to higher pore water pressures (e.g., groundwater rise, loss of capillary suction) or physical, chemical, and biological degradation of materials.

The stability of a slope is therefore based on the balance between driving and resisting forces. Driving forces promote movement, whereas resisting forces counteract it. The main driving force is gravity, whose effect is amplified by climatic and hydrological conditions. Consequently, landslides occur more frequently on steep slopes than on gentle ones. Water plays a crucial role, both by eroding slope toes and by increasing material weight or pore water pressures. Shear failure, and thus landslide initiation, presupposes two types of conditions:

- increase in shear stress, due to changes in external loads (earthworks, fills, construction, reservoirs, snow accumulation), or to the removal of stabilizing elements (erosion by rivers, wave action, frost shattering, tectonic movements);

- reduction in shear strength, caused by changes in soil physical–mechanical properties (infiltration, intense rainfall, rapid drawdown of reservoirs, freeze–thaw cycles).

Resistance to slope movement depends on the shear strength of the involved material, itself a function of cohesion and internal friction. Weathering, especially chemical alteration, progressively weakens materials, reducing their shear strength, which can further decline due to increased pore water pressures. In general, the shear strength of a material represents its capacity to resist shear stresses. It depends on the stress state as well as on the nature, texture, and structure of the material. In unconsolidated soils, shear strength arises from two main components:

- cohesion, resulting from mutual attraction (primarily electrostatic) between grains in contact;
- friction, controlled by grain size distribution, sorting, sphericity, and roundness, as well as by the soil fabric. Friction is higher in coarse-grained soils and in materials with angular grains.

Landslide Nomenclature

The geometric and morphological characteristics of a landslide are defined by the guidelines of the Working Party on World Landslide Inventory (1993), later confirmed by Cruden & Varnes (1996), and are illustrated in Fig. 1.1.1.

In general terms, the detachment niche of a landslide is the area of the slope from which the mobilized material has separated. It typically has an arcuate shape, wider in its uppermost part. The landslide track is the portion of the slope affected by downslope movement, while the landslide deposit refers to the accumulated material in the lower part of the slope, often convex in form and elevated with respect to the pre-existing topographic surface.

In more detail, considering complex movements such as rotational slides evolving into flows (Carrara et al., 1985), the following elements can be identified (Fig. 1.1.2):

Main scarp: steep surface that delimits the undisturbed area from the displaced mass; together with its subsurface continuation, it constitutes the rupture surface.

Minor scarp: steep surface within the displaced material, formed by differential internal movements.

Head: uppermost portion of the landslide mass, adjacent to the main scarp; often shows back-tilted surfaces and temporary ponds (head ponds).

Top: highest point of contact between displaced material and main scarp.

Toe of surface of rupture: generally buried boundary between the base of the rupture surface and the original slope surface.

Toe: outermost edge of the displaced mass, furthest downslope from the main scarp; often lobate and associated with groundwater seepage.

Tip: the point on the toe most distant from the crown point.

Foot: displaced material extending downslope beyond the rupture surface; tends to broaden laterally and reduce thickness and velocity, and is characterized by bulges, depressions, and fissures.

Main body: central part of the displaced material between the main scarp and the lower rupture limit.

Flank: lateral margin of the landslide.

Crown: undisturbed material adjacent to the upper part of the main scarp.

Original ground surface: slope surface prior to the landslide event.

Surface of separation: boundary between displaced and undisturbed material.

Displaced material: mobilized volume, either deformed or undeformed.

Zone of depletion: zone where the displaced material lies below the elevation of the original ground surface.

Left - right: when not using compass directions, “right” and “left” must be referred to an observer facing the landslide from the crown.

Fissures: cracks within the landslide mass or at its boundaries (crown or flanks), which may result from tension, shear, or compression; they can be longitudinal, transverse, or radial.

Transverse bulges and depressions: irregularities within the displaced mass, caused by variations in lithology, thickness, and velocity. They often display arcuate forms downslope and are associated with pore-water expulsion.

Lc: length corresponding to the chord of the rupture surface.

Vc: vertical component of Lc.

Hc: horizontal component of Lc.

L: total length of the area affected by the landslide.

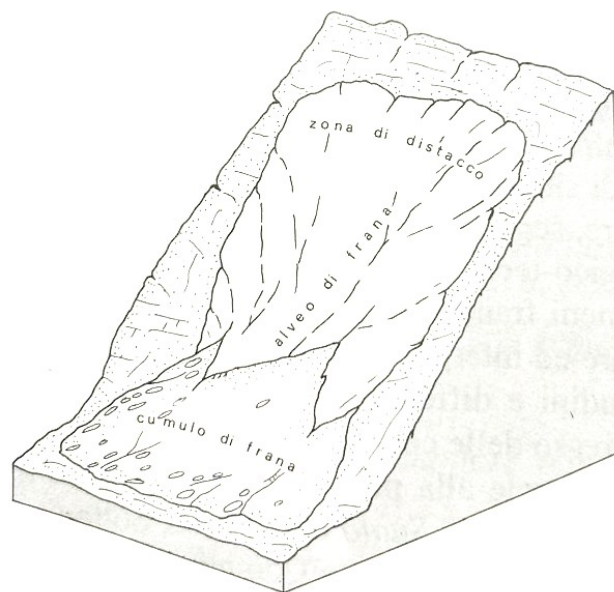


Figure 1.1.1: Basic nomenclature of a landslide (Vallario, 1992).

Classification Criteria for Landslides

Over time, numerous attempts have been made to classify landslide phenomena through schemes that account for the multiple factors that condition, promote, or trigger slope failures. However, considering simultaneously all geological, morphological, hydrogeological, structural, evolutionary, geotechnical, climatic, and anthropogenic aspects—while weighing the influence of each parameter on the triggering of a specific event—has proven to be of little significance. Such an approach would ultimately lead to the interpretation of every landslide as a unique case, distinct from all others.

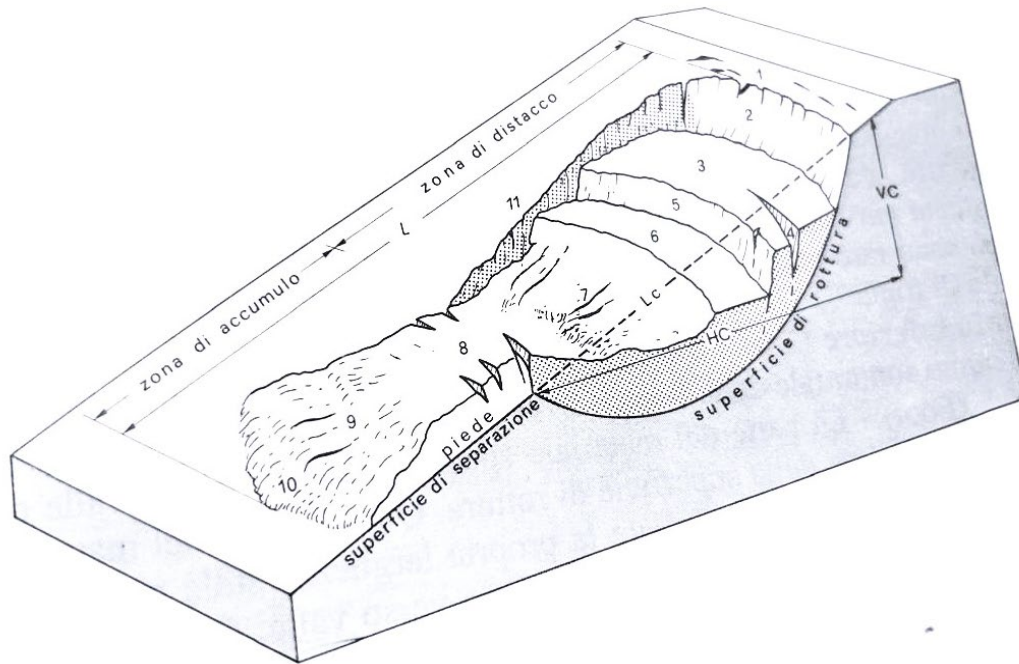


Figure 1.1.2: Nomenclature of a landslide. Each number corresponds to a specific element of the phenomenon: 1) crown; 2) main scarp; 3) head; 4) fissures; 5) minor scarp; 6) secondary landslide bench; 7) area of longitudinal cracks; 8) area of transverse cracks; 9) area of transverse bulges and, further downslope, radial cracks; 10) toe. (modified after Carrara et al., 1985).

A rational classification, in order to be effective, must be based on the criteria of scientific soundness, purposefulness, and practicality (Carrara et al., 1985). *Scientific soundness* is achieved by adopting objectively observable features; *purposefulness* is attained through the use of distinctive features that are relevant for prevention and stabilization; *practicality* is ensured by identifying parameters that are easy and immediate to obtain, even by non-specialists. Throughout the years, various classification criteria have been proposed, based on different factors:

1. Causes of movement: these cannot be considered a guiding feature due to the complexity and diversity of the factors capable of altering natural equilibrium. Thus, scientific soundness and practicality are not satisfied.
2. Duration and recurrence of the phenomenon: this parameter cannot be defined in the short term and is therefore unsuitable for immediate classification.

3. Type and mechanical properties of the material: although this represents a valid characterization criterion, it requires direct subsurface investigations and laboratory testing, making it poorly compatible with the principle of practicality.
4. Presence or absence of a pre-existing detachment or slip surface: this involves considerable difficulties in investigation and interpretation, limiting its practical contribution to classification.
5. Type of movement: this has been widely adopted by many researchers, as it can be observed with relatively low uncertainty through surface surveys and aerial photograph analysis. It describes the relative movement between the landslide mass and the in-situ material and is closely related to the morphology of both the slip surface and the landslide deposit. Overall, this criterion can be regarded as an excellent guiding factor in landslide studies.
6. Combination of guiding criteria: several authors have attempted to classify landslides by using multiple criteria simultaneously. However, this approach may generate confusion and therefore proves ineffective.

From these considerations, it can be concluded that the type of movement represents the primary guiding criterion for the classification of landslide phenomena.

Landslides can be classified according to their movement velocity. Varnes (1978) identified the categories reported in Table 1.1.1, while Hungr (1981) proposed additional classes of destructiveness related to displacement and movement velocity (Table 1.1.2). The fastest movements generally affect hard rock masses, where landslides occur at the end of the fracture process. In contrast, long-duration movements typically develop along slopes composed of plastically behaving rocks.

Table 1.1.1: Landslide velocity classification (Varnes, 1978).

Type	Velocity
Extremely slow	$v < 0.06 \text{ m/year}$
Very slow	$0.06 \text{ m/year} < v < 1.5 \text{ m/year}$
Slow	$1.5 \text{ m/year} < v < 1.5 \text{ m/month}$
Moderate	$1.5 \text{ m/month} < v < 1.5 \text{ m/day}$
Rapid	$1.5 \text{ m/day} < v < 0.3 \text{ m/min}$
Very rapid	$0.3 \text{ m/min} < v < 3 \text{ m/sec}$
Extremely rapid	$v > 3 \text{ m/sec}$

Table 1.1.2: Destructiveness classes based on movement velocity (Hungri, 1981).

Class of Destructiveness	Description	Velocity Range
No possibility of escape	Extremely rapid movement	$10 \text{ m/sec} < v < 100 \text{ m/sec}$
Loss of human lives, evacuation impossible	Very rapid to extremely rapid movement	$1 \text{ m/sec} < v < 10 \text{ m/sec}$
Evacuation possible, but destruction of buildings and permanent structures	Rapid to very rapid movement	$0.001 \text{ m/sec} < v < 1 \text{ m/sec}$
Partial damage to temporary structures	Moderate to rapid movement	$10 \text{ m/year} < v < 10^4 \text{ m/year}$
Reinforcement and restoration works feasible	Very slow to slow movement	$1 \text{ m/year} < v < 10 \text{ m/year}$
Engineering measures may ensure full functionality of permanent structures	Extremely slow to very slow movement	$0.01 \text{ m/year} < v < 1 \text{ m/year}$

Varnes Classification

The most widely used classification is that proposed by Varnes, first introduced in 1948 and later revised by the author in 1978. This system has proven particularly useful for preliminary investigations, as it allows different levels of detail without requiring assumptions about the triggering causes of the phenomenon. It can therefore be applied solely on the basis of surface observations. Varnes distinguishes five main classes: falls, topples, slides (further subdivided into rotational and translational), lateral spreads, flows, and complex landslides.

Each of these classes is further subdivided according to the type of material involved, differentiating between rock and unconsolidated soil. In this classification, a landslide is defined as: *“a gravity-driven movement, superficial or deep, rapid or slow, occurring in rock or soil.”*

To fully understand this classification, several additional aspects must be considered: the material involved, the spatial and temporal evolution of the movement, the relative age of the phenomenon, the state of activity.

The material involved is defined in the conditions prior to movement:

- rock mass: in situ rock with its structural discontinuities;
- rock: natural material with high cohesion, even after prolonged water immersion;
- unconsolidated soil: either coarse-grained (debris) or fine-grained (earth), composed of aggregates of unbound particles that can be separated by low stress or water contact.

For the spatial–temporal evolution we identify:

- stable (Fig. 1.1.3a);
- retrogressive (Fig. 1.1.3b): enlargement of the landslide area opposite to the direction of movement, caused by the retreat of the main scarp due to successive falls, topples, or slides, either immediately after scarp formation or during reactivation events;

- advancing (Fig. 1.1.3c): enlargement downslope or at the toe of the landslide, occurring through the development of multiple sliding surfaces or the forward propagation of a flow front;
- widening (Fig. 1.1.3d).

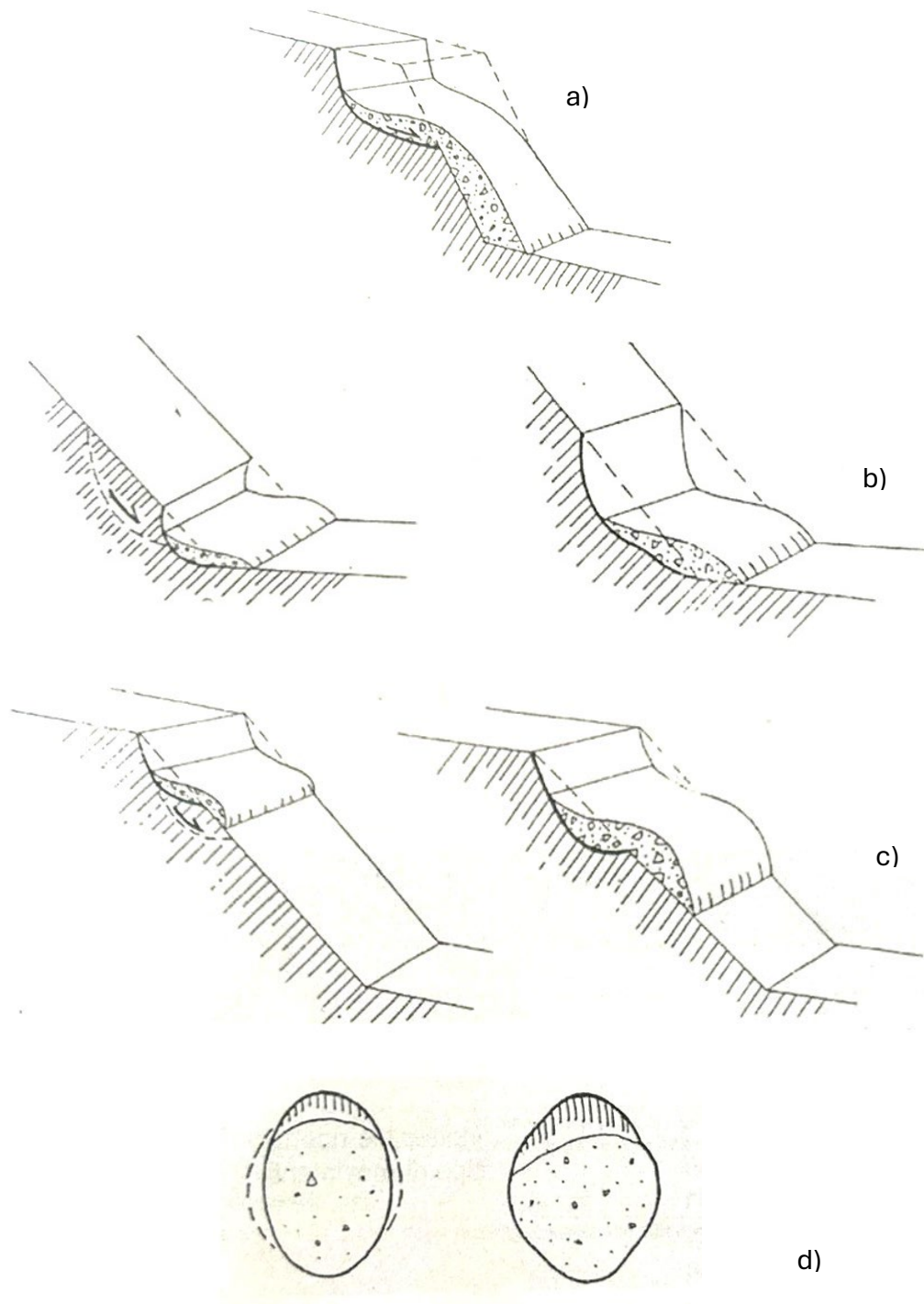


Figure 1.1.3: Distribution of landslide activity; a) stable; b) retrogressive; c) advancing; d) widening.

Depending on age, the following distinctions are made:

- Recent landslide: if the landslide occurred in the last decades on previously stable slopes;
- Ancient landslide: that phenomenon with no historical memory of occurrence;
- Fossil landslide (paleolandslide): developed in past geological periods.

The state of activity (Fig. 1.1.4) distinguishes:

- Active: landslide currently moving or affected by recent seasonal cycles;
- Dormant (quiescent): landslide showing no movement in recent times;
- Stabilized: landslide eliminated or reduced naturally or through artificial measures.

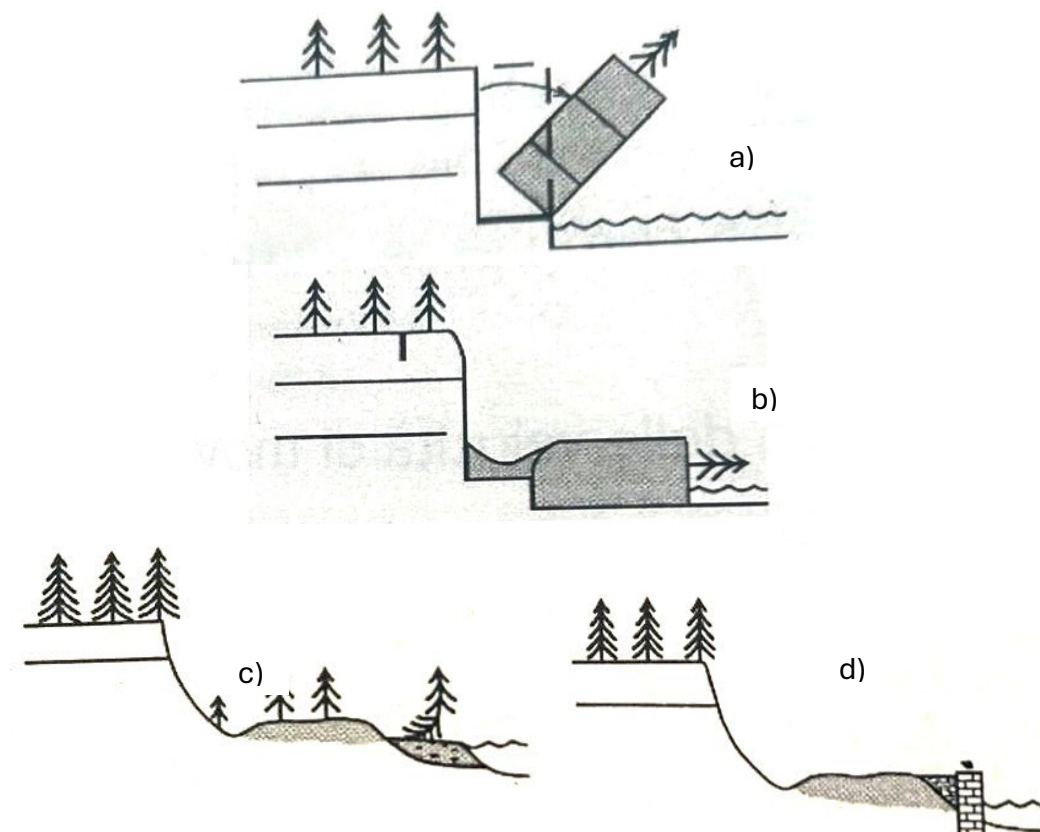


Figure 1.1.4: state of activity of a landslide; a) active; b) quiescent or dormant; c) naturally stabilized; d) artificial stabilized.

This classification has proven particularly valuable for preliminary surveys, as it enables detailed analysis without addressing triggering factors, and it can be effectively applied through surface observations alone.

Rockfalls

Rockfall landslides (Fig. 1.1.5) are characterized by the displacement of material in free fall, followed by subsequent movement through bouncing and rolling of rock fragments, which may undergo complete fragmentation. They can occur in lithoid, incoherent, or semi-coherent materials that suddenly detach from the slopes. These phenomena are usually observed in slopes affected by pre-existing discontinuities (faults, bedding planes) or along newly formed surfaces where detachment takes place.

Such events are sudden: the velocity of movement is high, and no clear precursory signs are generally observed. The movement predominantly follows the vertical component of displacement; therefore, specific morphological conditions are required, such as steep slopes or marked slope breaks. The accumulation zone is usually located at the foot of the slope and generally does not participate in further evolutionary processes, unless the slope forms a cliff or lies at the base of a watercourse. In these cases, the deposit may provide natural protection against erosional processes or obstruct the channel, forming a temporary lake. This type of landslide is primarily associated with an increase in shear stresses.

Rockfalls are most commonly observed in massive or thickly bedded lithoid rocks, often fractured and karstified, although they may also occur in poorly coherent or deeply weathered rocks, where the detached mass disintegrates before reaching the ground. Typical materials involved include sandy–conglomeratic sequences, debris accumulations, highly tectonized sedimentary rocks, as well as weathered and disintegrated igneous and metamorphic rocks. In the case of rock masses, the rupture surface is usually planar and vertical, whereas in incoherent or semi-coherent rocks it may display a cycloidal pattern.

The main triggering causes include thermal excursions, freeze–thaw cycles, erosional action of surface waters at the slope base, seismic loading, destabilizing effects of root systems, and anthropogenic activities.



Figure 1.1.5: a) schematic illustration of a rockfall; b) schematic illustration of a fall occurring in poorly consolidated or weathered rocks (Vallario, 1992).

Topples

Topple failures (Fig. 1.1.6) are characterized by the rotation of material around a point located below the center of gravity of the mass. The phenomenon may subsequently evolve into a rockfall or a slide. The movement can occur in isolation, associated with pre-existing fractures, or more rarely along newly formed surfaces. These landslides are widespread in rock masses with steep slopes or in lithoid rocks where discontinuity patterns define blocks in precarious equilibrium. Blocks detached by toppling may further fragment into smaller pieces, which generally travel greater distances from the point of detachment and may roll down the underlying slope.

Predisposing factors are almost always structural or stratigraphic in nature, typical of rock masses affected by vertical fractures or bedding joints. Toppling can also occur where lithoid rocks overlie plastic, deformable, and erodible substrates. The triggering factors are similar to those of rockfalls, including thermal variations, freeze–thaw processes, surface water erosion at the slope base, seismic loading, and anthropogenic disturbances.

Although less common, topples can also occur in non-lithoid rocks, such as gravels with variable clay or sand content, fluvial, lacustrine, or marine conglomerates exposed in vertical cliffs or along morphological terraces. In these cases, triggering factors may include wave action or fluvial currents undermining the slope toe, seismic shocks, or artificial vibrations. Detachment always takes place along newly formed surfaces.

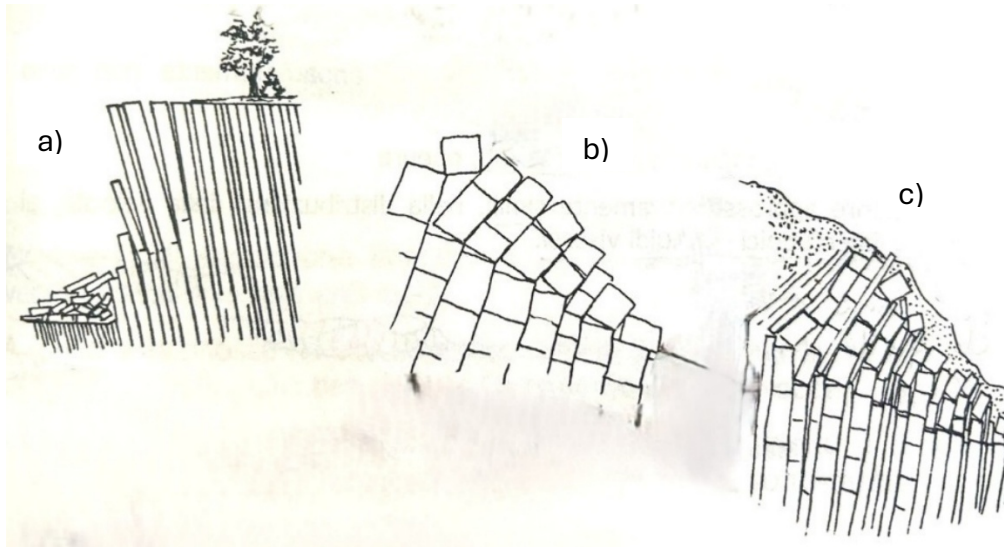


Figure 1.1.6: Schematic representation of toppling failures; a) flexural toppling; b) block toppling; c) flexural block toppling.

Slides

Slides occur when the shear strength of rock materials is exceeded along newly formed or pre-existing surfaces (such as stratigraphic or tectonic contacts, boundaries between cover deposits and bedrock, or interfaces between altered and intact portions of a rock mass), or along mechanically weaker levels of stratigraphic or tectonic origin.

The landslide body may fragment into several blocks, separated by longitudinal and transverse fractures. Following an initial stage, often characterized by significant displacements, the process may evolve into the progressive collapse of the slope. Within slides, two main types can be distinguished: rotational and translational.

Rotational Slides

Rotational slides (Fig. 1.1.7) are mass movements that occur through rotation around a point located outside the slope and above the centroid of the moving mass. The slip surface is generally arcuate, concave upward, and relatively regular, allowing a reliable prediction of its trajectory even within the rock mass. This phenomenon can occur in both rock masses and soils, with the regularity of the slip surface being related to the homogeneity of the involved material. In more competent rock masses, the landslide body tends to preserve its configuration after movement, whereas in more plastic rocks the displaced mass tends to deform and disaggregate into several blocks bounded by secondary slip surfaces.

This type of landslide is particularly common in sedimentary sequences with predominantly plastic behavior, such as flysch deposits, but it is also frequently observed in altered portions of igneous and metamorphic rocks, such as granites and schists. In the crown area, collapse cracks parallel to the main scarp are typically observed, located between the scarp itself and the upper topographic surface of the displaced mass. The head of the slide body often displays a back-tilted surface, where small head ponds may form. The lower portion of the landslide body generally tends to spread laterally, overlapping the underlying slope.

Triggering causes are often associated with infiltration waters from intense rainfall events or from the rupture of water supply networks. Additional causes may be linked to the direct or indirect effects of earthquakes, which can induce increased pore-water pressures due to the progressive rise of the water table following ground shaking. Anthropogenic actions—such as cuttings, trench excavations, or slope overloading—also represent significant destabilizing factors.

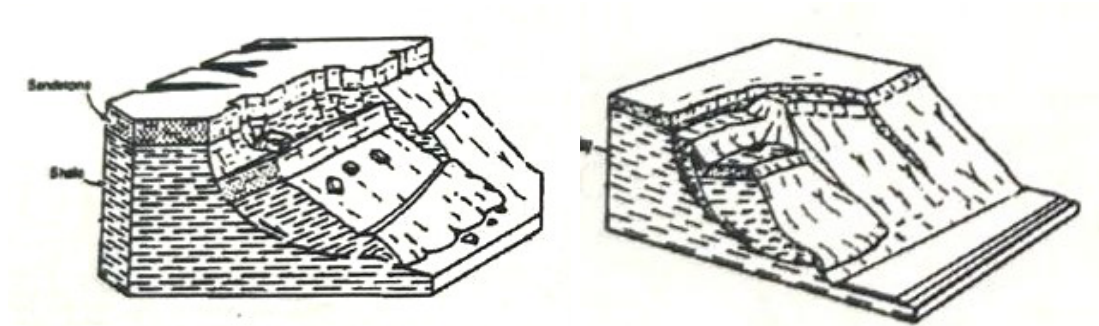


Figure 1.1.7: Schematic illustration of a rotational landslide.

Translational Slides

In translational slides (Fig. 1.1.8), displacement occurs along a relatively smooth pre-existing discontinuity surface, such as a bedding plane, a fracture, a fault or thrust plane, a contact between intact and weathered rock, or between bedrock and overlying debris. The key predisposing condition is that the discontinuity surface is inclined in the same direction as the slope (dip-slope condition), with an inclination equal to or lower than that of the slope itself.

The phenomenon is triggered by a reduction in frictional resistance along the discontinuity surface, and movement generally occurs at moderate velocity in the direction of maximum slope gradient. This type of landslide is commonly observed in stratified rock sequences with alternating competent and plastic layers, along contacts between rigid rock masses overlying deformable plastic substrata, or as planar sliding of debris covers resting on bedrock.

The triggering causes, either natural or anthropogenic, are related to a decrease in shear resistance along discontinuity surfaces or to sudden increases in shear stress, such as those induced by seismic events, which can initiate displacement of rock masses already in precarious equilibrium. In unconsolidated materials, instead, the main causes include increased water content, undercutting at the slope toe, and surcharge loading. Morphologically, the crown area typically exhibits a sharp, nearly vertical scarp, while the landslide body is fragmented. Along the flanks, a well-defined detachment surface between the displaced material and the in-place mass is not always evident. A distinctive feature of this

type of movement is the occurrence of predominantly transverse cracking, associated with decompression processes.

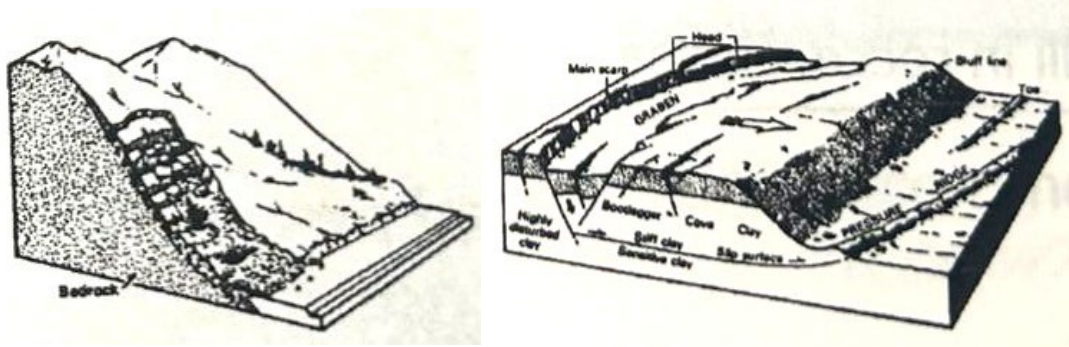


Figure 1.1.8: Schematic illustration of a translational landslide.

Lateral Spreading

Lateral spreading (Fig. 1.1.9) develops under specific conditions, typically when a fractured rigid rock mass overlies a plastic substratum. Deformation initiates within the underlying plastic layers, which deform differentially, thereby inducing movement in the overlying rigid rocks, which disaggregate into blocks. The movement may occur under relatively low levels of stress, and its main component is horizontal displacement. Velocity is generally slow, although it may increase depending on the inclination of the separation surface between the two materials and their contrasting mechanical behavior. As a result of the movement, the displaced mass appears heterogeneous, with sharply defined separation surfaces between the individual blocks.

The principal triggering factors include increases in pore-water pressures within the plastic substratum or a rise in piezometric load within the overlying rigid rocks, particularly in cases of high permeability. This type of phenomenon may also occur in unconsolidated fine-grained soils.

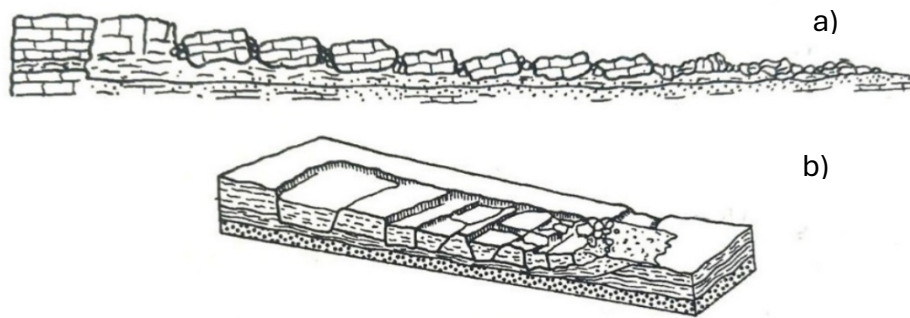


Figure 1.1.9: Schematic illustration of lateral spreads; a) absence of a recognizable basal slip surface; b) movement controlled by plastic deformation of the underlying material.

Flows

Flows are complex types of landslides that can display variable characteristics and velocities depending on the materials involved. They can be divided into flows affecting rock masses and flows occurring in soil-like materials.

Flows in rock masses (Fig. 1.1.10) generally involve slow movements associated with plastic and differential deformations of slopes. Their velocity, typically low, is closely related to water content. The rock mass is often intersected by numerous discontinuities that facilitate differential displacements and, consequently, the overall movement. This type of phenomenon is characteristic of stratified rock sequences with vertical or steeply inclined bedding, and of slopes with medium to high gradients.

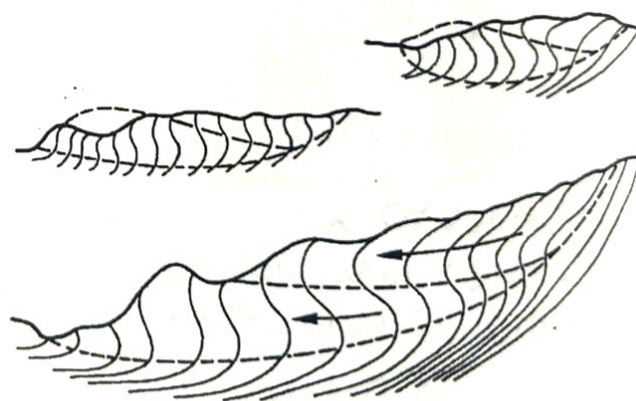


Figure 1.1.10: Rock flow phenomena (Vallario, 1992).

Flows in unconsolidated materials (Fig. 1.1.11) include a wide range of cases with highly variable characteristics. They are plastic movements with velocities that vary across different parts of the landslide body. The boundaries of such landslides can be either well-defined or diffuse, depending on whether differential displacements gradually decrease. Sliding surfaces are often poorly defined, temporary, and continuously evolving. Velocities are extremely variable, depending on soil type and geological-morphological conditions: the finer the material, the higher the velocity.

Depending on the type of material involved, flows include: debris flows, debris avalanches, block flows, shallow soil flows, sand or silt flows, rapid earth flows, gully flows, dry sand flows, and loess flows. These phenomena occur in weathered rock masses, alluvial covers, sandy, clayey, or silty sediments, and in deposits from previous landslides.

The landslide body typically consists of a fragmented mass in continuous downslope movement, progressively fed from upslope and laterally. In the source area, transverse collapse cracks, bowl-shaped depressions, and occasionally multilobed detachment zones can be observed. Downslope, longitudinal tension cracks parallel to the flanks develop as evidence of movement. The lower portion tends to spread out, reducing velocity and thickness. Here, the displaced mass acquires a lobate morphology, with frequent radial cracks and water outflows caused by compression of saturated materials. Movement occurs along multiple failure surfaces without a sharp separation between moving mass and substratum. Within the landslide body, velocities are not uniformly distributed: outer portions can move from a few meters up to 30–40 m per day. In coarse-grained saturated soils, typical processes include: rapid debris flows, slow soil flows, very rapid debris avalanches, extremely slow shallow flows, and rapid block flows. In fine-grained saturated soils, processes include: rapid to very rapid saturated sand or silt flows, very rapid quick earth flows, earth flows ranging from very slow to rapid, extremely rapid loess flows (often earthquake-induced), and dry sand flows (rapid to very rapid). Flows in

fine-grained saturated soils are often extremely fast, destructive, and catastrophic. The material, characterized by high viscosity, moves with velocity controlled by slope gradient and water content. It often follows pre-existing erosion gullies, and at the slope base it spreads into fan-shaped deposits in flatter transition areas.

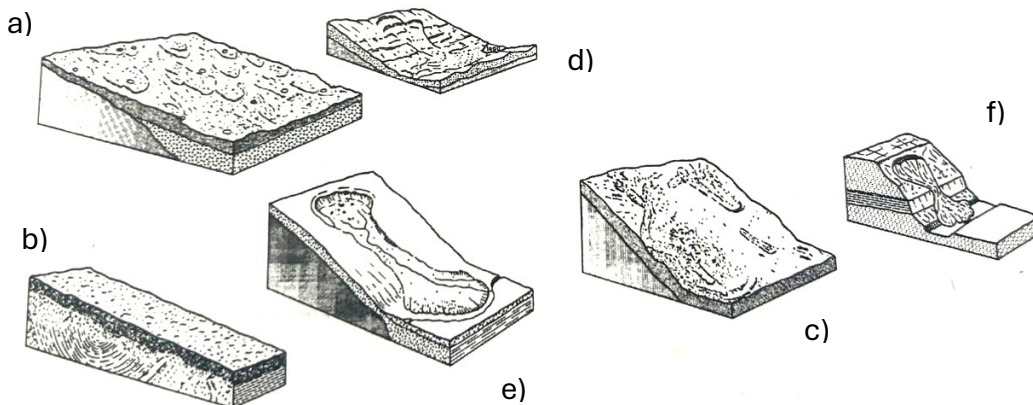


Figure 1.1.11: Examples of flows in loose material; a), b), c): coarse-material flows; d), e), f): fine-material flows.

Complex Phenomena

Complex landslide phenomena (Fig. 1.1.12) are characterized by movements resulting from the combination of two or more types of landslides previously described. The most frequent combinations include: rockfall – debris flow; rotational slide – flow; rotational slide – earth flow; rotational slide – topple; translational slide – flow. With the Cruden and Varnes (1996) classification, complex landslides are excluded from the main classification and this type is instead incorporated into the activity style.

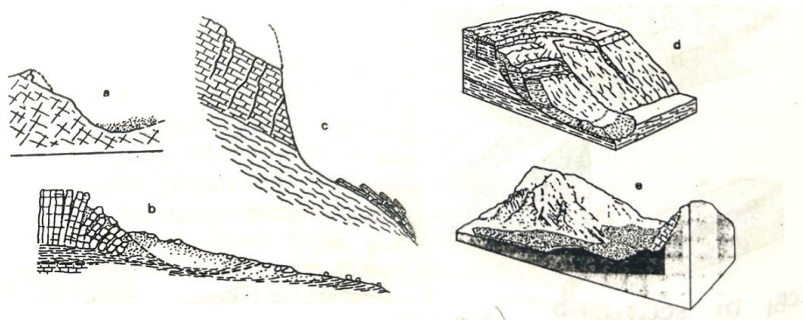


Figure 1.1.12: Examples of complex landslide types (Vallario, 1992).

1.2 Deep-Seated Gravitational Slope Deformations (DSGSDs)

Deep-seated gravitational slope deformations (DSGSDs) are mass movements involving large rock volumes, characterized by spatial and temporal scales intermediate between those of typical landslides and tectonic processes. A possible definition identifies DSGSDs as long-term deformation phenomena (lasting up to tens of thousands of years) that displace rock masses of considerable volumes (up to the order of km^3) along pre-existing or newly formed discontinuities. These processes produce visible geomorphological effects or instrumentally detectable movements within the morphodynamic framework of ridge–slope–valley systems.

Due to their large dimensions, determining the stress state at depth, assessing the mechanical behavior of rock masses, and developing a realistic kinematic model are extremely complex tasks. While it is generally possible to define the lithostructural and geomorphological framework of DSGSDs, their geotechnical characterization remains highly challenging. The mechanical properties of rocks, and therefore the deformation mechanisms, may be influenced by scale-dependent factors (Goguel, 1978), such as vaporization of underground fluids, reduction of friction, and high pressures along rupture surfaces, which may cause melting of crystalline rocks or dissociation of CaCO_3 into CaO and CO_2 .

Favorable lithostructural settings for the onset of DSGSDs (Fig. 1.2.1) include:

1. Superposition of brittle rock formations over ductile rocks.
2. Alternation of brittle and ductile lithotypes with variable thickness.
3. Lateral confinement of brittle rocks overlying ductile rocks.

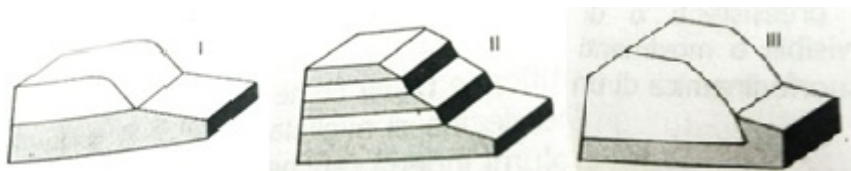


Figure 1.2.1: Favorable lithostructural settings for the initiation of Deep-Seated Gravitational Slope Deformations (DSGSDs).

According to Varnes' classification (1978), three main types of DSGSDs can be recognized: rock flows, lateral spreads, and rock block slides.

- Rock flows (*sackung* in the international literature) occur in fractured lithologies forming steep and elevated reliefs. Deformation is distributed along fractures of various sizes, without necessarily defining a single continuous shear surface across the entire deformed zone. The movement is generally very slow, with velocity distributions comparable to viscous fluids. Typical morphological expressions include bulging, depressions, and ridge splitting. Some schematic representations of rock flows were proposed by Hutchinson, 1988 and are shown in Figure 1.2.24.
- *Lateral spreads* (Fig. 1.2.3) may develop without a well-defined basal shear surface or a localized plastic deformation zone. Although the mechanisms remain not fully understood, this type of movement is associated with clear morphological evidence, especially along ridges. In cases where brittle rocks overlie ductile successions, plastic–viscous deformation may induce fragmentation of the rock mass, which translates predominantly with horizontal displacement.
- *Rock block slides* (Fig. 1.2.4) are characterized by movements along a clearly defined surface, either pre-existing or newly formed. The morphological effects are closely related to the magnitude of displacements and the size of the displaced blocks. Collapse occurs when the rock mass becomes kinematically free and the inclination of discontinuities exceeds the available shear strength.

DSGSDs involve the entire ridge–slope–valley system and play a significant role in shaping structural margins in areas of recent uplift. Since the 1960s, several authors have proposed considering them as a distinct category of mass movements rather than landslides, given their scale dependence and particularly complex evolutionary mechanisms. Nevertheless, terminology has not always

been uniform, and some authors still classify DSGSDs within the broader category of large landslides.

An exhaustive and universally accepted definition has not yet been established. A widely cited formulation describes DSGSDs as long-term deformation phenomena (lasting up to tens of thousands of years) that displace significant rock volumes along pre-existing or newly formed discontinuities, producing visible geomorphological effects and instrumentally detectable movements within ridge–slope–valley morphodynamics. While their lithostructural and geomorphological setting can often be outlined, evaluating geotechnical aspects and developing reliable models remains extremely difficult.

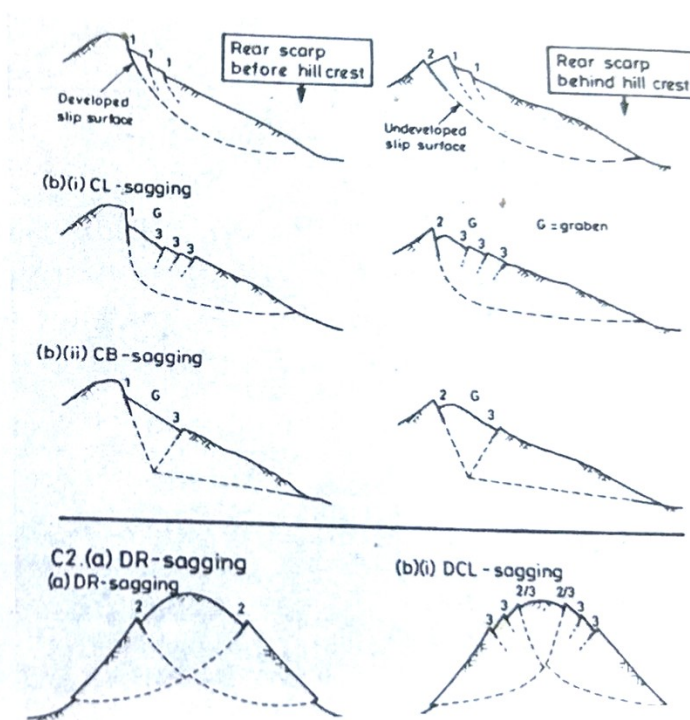


Figure 1.2.2: Illustrations of rock flow types (Hutchinson, 1988).

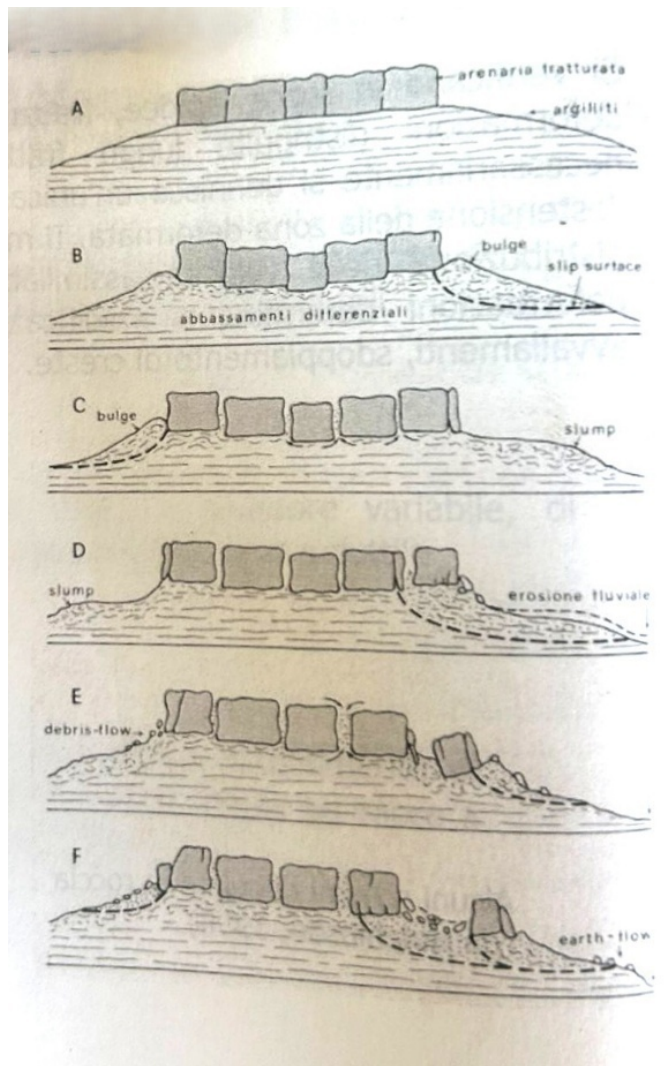


Figure 1.2.3: Evolutionary model of lateral spreads. Superposition of limestone blocks on a clayey substrate (Cancelli et al., 1987).

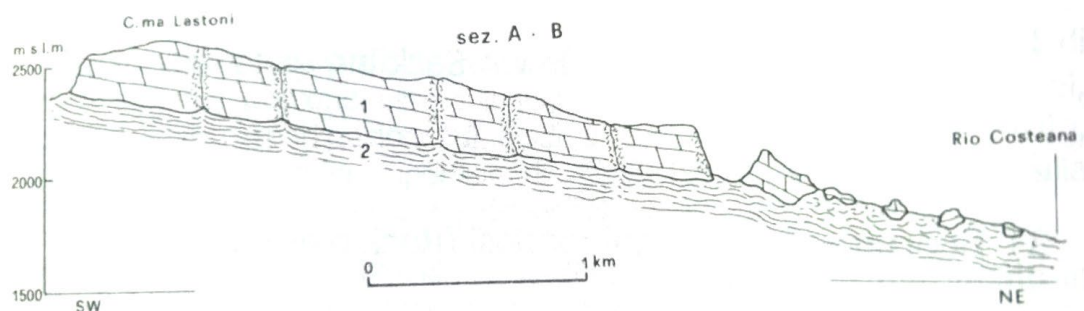


Figure 1.2.4: Schematic geological section illustrating rock block slides. (Menotti et al., 1990)

The geomorphological effects induced by DSGSDs are the most widely used criteria for identifying affected areas. These effects manifest throughout the ridge–slope–valley system and are often associated with shallow landslides whose distribution, genetic processes, and evolution are strictly connected to deep-seated movements.

- **Ridge sector:** detectable features include planimetric and altimetric variations, semi-open tension cracks, and trenches oriented in arcuate or sub-angular patterns. These cracks typically widen toward the transition between ridge and slope and may be conditioned by tectonic mesostructural discontinuities. Ridge duplications and subsidence are also common: ridge duplications produce parallel or offset crests separated by depressions, whereas subsidence results in the lowering of the original crest, leaving the marginal culminations as secondary ridges. Erosional processes (glacial, periglacial, or karstic) can further remodel these forms.
- **Slope sector:** tension cracks are frequent near the upper slope, while the intermediate zones are often characterized by counter-slopes and bulging, producing irregular slope profiles. Counter-slopes are typically associated with depressions oriented orthogonally to the maximum gradient, partially infilled by colluvium from overhanging slope sections.
- **Piedmont sector:** this transitional zone between slope and valley floor often displays gentler gradients where rigid lithotypes overlie ductile lithologies. The transition may be abrupt or gradual, often mediated by talus deposits generated by slope erosion. Depressions, counter-slopes, and bulging are also common here, marking the toe of the deformed zone or accumulation areas of displaced rock masses. Differential subsidence of ductile units beneath the piedmont may further destabilize overlying slopes, favoring deep-seated deformation. Retrogressive shallow landslides migrating from the valley floor toward the slope base are often associated with this process.

- **Valley floor:** this sector often hosts permanent or temporary stream damming, channel diversions, and terrace deformation. Recognition of deformed terrace surfaces allows reconstruction of base levels and identification of major deformation phases.

Morphological evidence is strongly related to the type of movement and its evolutionary stage. Like shallow landslides, DSGSDs can be classified as active, dormant, or inactive.

The interaction between geological, paleotectonic, neotectonic, and geomorphological processes creates morphostructural settings favorable to DSGSDs. These conditions may include the superposition, alternation, or confinement of brittle and ductile rock units, with stratigraphic or tectonic contacts. The geometry, thickness, and frequency of discontinuities, as well as the proportion of brittle versus ductile units, are key parameters for identifying areas prone to deep-seated deformation (Guida & Longo, 1988).

Although strong topographic reliefs and steep slopes favor DSGSD development (Dramis, 1984), large elevation and slope angles are not sufficient by themselves. Their formation is instead linked to complex evolutionary histories involving tectonic uplift, base-level changes, reorganization of drainage networks, and slope destabilization by erosion or glacial retreat. For example, in alpine environments, DSGSDs are often associated with post-glacial valley dynamics, where stress release due to glacier retreat triggered slope decompression.

Climatic fluctuations also played a crucial role: during cold Pleistocene intervals, rapid evolution of fault scarps and accumulation of detrital material frequently dammed valleys or sealed slope bases. Subsequent erosion of these deposits increased local relief and promoted deep-seated instability.

Among the most relevant triggering factors are extreme rainfall events and seismic activity. Intense precipitation increases pore water pressure within fractured rock masses, reducing shear strength and possibly leading to

catastrophic collapses. Strong earthquakes may generate normal-to-slope stresses, abrupt topographic changes, and liquefaction phenomena, which can activate or reactivate DSGSDs, as observed in areas struck by high-magnitude seismic events.

Identifying DSGSDs is particularly challenging because their deformational signatures are often subtle, especially when movements are inactive or of ancient origin. Their morphodynamics may include long phases of quiescence followed by sudden catastrophic collapses. Frequently, only marginal portions of affected areas remain active, often expressed through anomalous shallow movements that are not immediately recognized as part of larger-scale processes.

For this reason, the recognition of hazard-prone areas requires targeted investigations and integrated monitoring. Field surveys, geomorphological mapping, and geophysical techniques can help constrain the geometry and geomechanical parameters of the involved rock masses. Monitoring strategies include precise geodetic and topographic surveys, GPS measurements, high-resolution distance measurements, and fracture displacement monitoring. Additional information can be derived from microseismic activity, variations in local electric fields, and hydraulic conductivity changes (Rizzo, 1984).

From a hazard perspective, DSGSDs are particularly critical because their slow evolution often conceals their true risk potential. Entire settlements may be located on or near active deformation areas without apparent evidence of instability. Furthermore, urban expansion frequently extends into peripheral sectors of DSGSDs, which are usually the most active and rapidly evolving zones.

1.3 Monitoring Techniques

Geological monitoring is crucial to define the evolution of a phenomenon and allows the development of forecasting models aimed at identifying appropriate risk mitigation measures and planning land use in situations that are difficult to permanently counteract with stabilization works. The term “*monitoring*” refers to “*the periodic and systematic measurement of chemical, physical and biological parameters, by means of specific instruments, in order to control the situation or the evolution of even complex systems*” (s.d.). Monitoring, particularly when related to landslide phenomena, must be carried out by following specific steps: first, a bibliographic study of the instabilities that have affected the area and of its geology; secondly, the selection of the parameters that are fundamental to stability analysis; and finally, after the monitoring campaign, assessment of the mitigation works that can be used to stabilize the area affected by the ongoing processes. It should be emphasized that monitoring should not be limited or restricted only to the slope; moreover, its temporal extension does not end once the stabilization work is carried out, since the latter must also be maintained and monitored to assess their efficiency over time.

The characterization of landslide phenomena, along with their potential triggering and development, can only be carried out starting from the theoretical study of the event. It is necessary to undertake bibliographic research of a geological, geomorphological, hydrogeological, engineering-geological, and geotechnical nature, as well as consult basic and thematic geological maps in order to gather all the historical knowledge elements that are of considerable interest in reconstructing the sequence of events and their meaning in the natural physical environment and in the land use where the event occurred. In addition to scientific literature, it is possible to acquire knowledge from the technical offices of public authorities that oversee the construction of public works and land management, as they are institutionally responsible for intervening in the event of landslides interfering with works and human activities. To achieve the stated goal, it is necessary, in successive working phases, to carry out an

adequate reconstruction of geological conditions and the study of recent geomorphological evolution; then proceed with the reconstruction of the slope and landslide geometry by direct and indirect methods, determine the physical–mechanical properties of soils in primary deposition and those mobilized, formulate interpretative models, perform stability checks on an analytical and geomorphological basis, and finally identify the type of landslide phenomenon and design possible intervention works suitable for restoring the altered equilibrium and rehabilitating the area. Ultimately, after having carried out theoretical studies and surveyed the landslide area and its surrounding zones, it will be necessary to subject the landslide phenomenon to monitoring. The geomorphological and engineering–geological field survey must always be preceded by the analysis of aerial photographs, which allows a global view of the area and provides an overview of the salient evolutionary events that characterize it. After this initial knowledge phase, a detailed field survey will be conducted, supported by a recent topographic survey at an appropriate scale. The involvement of a surveyor is required to perform a detailed survey of the landslide area and the immediately surrounding areas. On the new topographic map, all elements suitable for an adequate interpretation of the phenomenon will be mapped, such as scarps, cracks in the landslide mass, crown or adjacent zones near the landslide channel, possible counter-slopes, bulges, and transverse depressions. Through monitoring, it is essential to keep track of any differential movements by frequently surveying the position of structures involved or at risk of being involved, and it is useful to verify the displacement of the landslide toe relative to downstream or lateral structures, as well as to map shape variations at the landslide's toe.

1.3.1 Engineering-geological monitoring

Engineering geological monitoring serves to identify the relationships between groundwater and the landslide slope, runoff water and infiltration, geological conditions and slope evolution, as well as the positioning of any wells and springs and the control of static and dynamic groundwater levels, thereby contributing to a more targeted definition of subsequent investigations. The engineering–geological analysis should aim at recognizing the application-related issues triggered by anthropogenic land use and their possible future effects within a highly evolving framework. The mapping must be completed with interpretative geological cross-sections highlighting local stratigraphic, structural, geomorphological, and hydrogeological conditions, to produce a basic geological and geomorphological map and a complete inventory of landslide phenomena, following standardized criteria. In addition to surface surveys, which allow the definition of surface geometry (slope and landslide area), it is essential to identify the depth of the sliding surface, the thickness of the landslide deposit, the possible presence of an older landslide deposit beneath the current one, and the presence of aquifers—that is, all those elements that enable the reconstruction of an interpretative model, accompanied by the parameterization of the mechanical strength of the materials forming the landslide body and the in-situ rocks.

In landslide studies, it is of great importance to have not only data from direct and indirect surveys carried out after the event, but above all continuous monitoring data capable of recording temporal variations of significant parameters directly linked to the physical environment and to the landslide phenomenon. This type of monitoring is fundamental not only for preventing possible harmful effects and controlling the effectiveness of intervention works, but also for interpreting kinematics and recognizing the evolutionary models in progress.

The parameters that must be monitored by such a system concern some characteristic elements of the specific event, among which there are the

following measurements: displacements and surface deformations of the moving mass, displacements and deformations of structures located in the landslide area, displacements along the failure surface, variations in the free surface of possible aquifers, variations in pore pressures, and the continuous recording of rainfall, air temperature, and humidity.

To protect public safety, in some landslide cases visual inspections or the implementation of automatic alarm systems is required, to detect sudden increases in displacement rates, often following particular rainfall events or seismic shocks, or due to retrogressive evolutions that increase the load upslope, thereby feeding the moving mass from above. The realization of the monitoring system essentially depends on the knowledge framework reconstructed from geological and morphological surface surveys and from the detailed analysis of the landslide event. Ultimately, monitoring should not be limited only to the design phase but also it should be extended to the construction and operational phases of stabilization works. In particular, during the design phase it is necessary to develop the geotechnical model of the subsoil, estimate safety conditions, and characterize ongoing processes. During construction, it must be ensured that the previously assumed model is consistent with reality, and the effects induced by the construction of the work must be characterized. During operation, it is necessary to check safety conditions over time and characterize the evolution of possible kinematic processes for the activation of preventive alarm systems.

Monitoring activities require a data acquisition phase regarding factors influencing slope stability (Fig.1.3.1.1). In particular, slope stability is affected by:

1. External factors: weather conditions (precipitation, temperature), surface water runoff and its variations, reservoir water level (in the case of artificial reservoirs), vibrations (seismic and blasting), and changes in slope geometry.

2. Slope behavior: displacement or deformation (at the surface and at depth), hydraulic conditions (pore pressures, suction, drainage flows), soil properties (permeability, seismic velocity), failure phenomena.
3. Structural behavior: loads transmitted to the ground and structural deformations.

Investigations must be planned based on economic resources, available time, and the type of issue, depending on the context. In this way, it is possible to define an intervention strategy, the variables to be monitored, the monitoring frequency, and the critical points. The final result of monitoring activities is based on data processing, obtained through the instrumentation installed in the field. For the definition of the aforementioned variables, whose variation is closely related to the loss or maintenance of slope stability, both in-situ instrumentation and laboratory tests are used. Depending on the type of variable investigated, different instruments are employed.

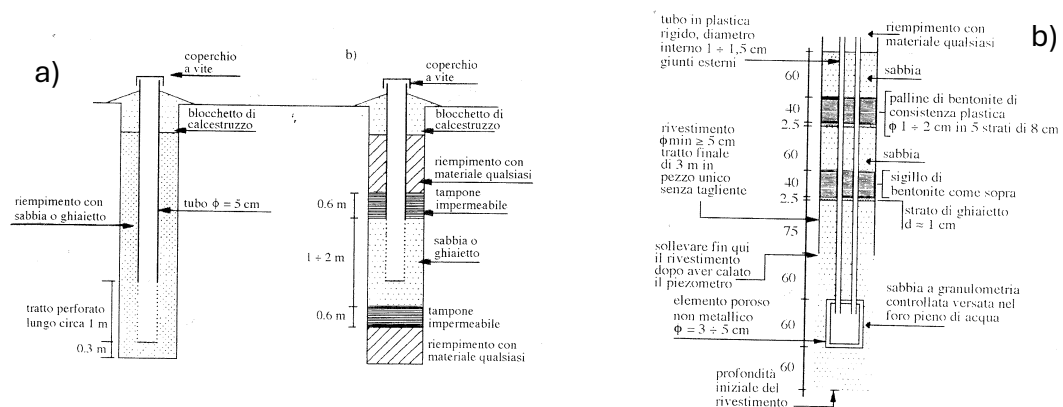


Figure 1.3.1.1: Schematic representation of the physical quantities to be monitored in the case of landslide phenomena. The water content and pore pressures vary in relation to rainfall infiltration and cause both surface and internal slope displacements (Pagano, 2009).

Pore Pressure and Piezometers

Pore pressure provides fundamental information about the groundwater regime and allows the monitoring of changes induced by natural or anthropogenic disturbances. Its measurement is performed using piezometers, which can be of

The type of piezometer used is therefore closely related to soil permeability and determines the responsiveness with which equilibrium is reached following variations in pore pressures.



Water Content and Suction

36

water exchange but prevents air entry—and a manometer or vacuum gauge that records pressure changes. As the soil dries, it withdraws water through the porous cup, generating a negative pressure inside the tube, which is then detected by the gauge. Conversely, when the soil is saturated, suction is nearly zero, and the tensiometer records values close to zero.

The suction of the liquid phase can be measured directly, using devices similar to piezometers. Alternatively, it can be estimated indirectly, either by measuring the vapor pressure of the fluid in equilibrium with the soil water, or by determining the water content of a porous medium placed in hydraulic equilibrium with the soil (e.g., filter paper or thermal probes).

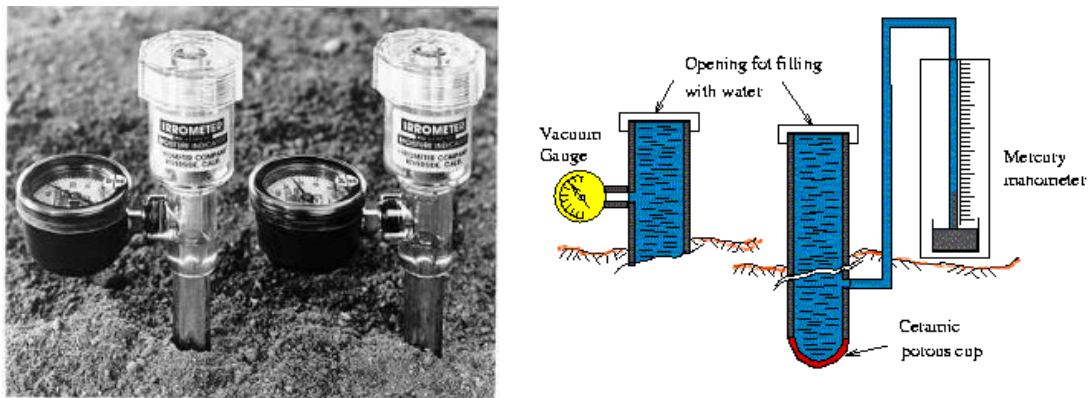


Figure 1.3.1.3: Image (left) and schematic representation (right) of a tensiometer (Ahmad et al., 2017).

Deep-Seated Deformations and Inclinerometers

Deep-seated movements occurring along the slip surface cannot be inferred solely from surface data. Nevertheless, their analysis is crucial for understanding the internal mechanisms of landslides and for determining both the depth and geometry of the rupture surface. The selection of instruments for monitoring surface and subsurface displacements must be made carefully, considering both effectiveness and economic feasibility. Among the most widely used instruments for detecting and monitoring horizontal displacements at depth are inclinometers (Fig. 1.3.1.4). The inclinometer casing must extend below the slip surface, with its base anchored several meters into a stable

bedrock. The casing consists of two concentric circles defining its thickness. The inner surface is not smooth but features four grooves, arranged in opposing pairs, one of which is aligned with the maximum slope direction. Inclinator casings are installed in boreholes and subsequently grouted, to ensure that the measured displacements correspond to soil movements rather than to casing deformations. The grooves serve as tracks for the wheels of the inclinometer probe, ensuring consistent alignment. The probe itself is attached to a graduated cable and a pulley with a locking mechanism, allowing controlled insertion and retrieval along the casing tracks without oscillations. Inclinator measurements are acquired in pairs: first along one axis (A–A+), then along the orthogonal axis (B–B+). Data acquisition can be carried out either continuously, by sliding the probe along the full length of the borehole, or at fixed, regular intervals—the latter being the most commonly adopted method.

Measurements are taken progressively at increasing depths: the probe is advanced by a predefined step, locked in place, the signal is allowed to stabilize, and the reading is recorded. This procedure is repeated until the bottom of the borehole is reached, yielding n measurements (Fig. 1.3.1.5).

Inclinometers can also be installed as fixed systems, with probes cemented in place at predetermined depths, providing automatic data acquisition. It is important to note that inclinometers do not directly measure displacements, but rather angular deviations from the vertical, which at the initial time (t_0) was 90° relative to the ground surface. Consequently, horizontal displacement must be calculated by transforming the angular deviation into a linear shift, obtained by multiplying the reading interval by the sine of the deviation angle.

Inclinator data allow the reconstruction of both the geometry and depth of the slip surface. To ensure reliability, at least three measurements are required, to verify data consistency and confirm that boreholes extend to the correct depth. Results are typically plotted as graphs correlating global or horizontal displacements with depth, enabling identification of stable versus moving zones.

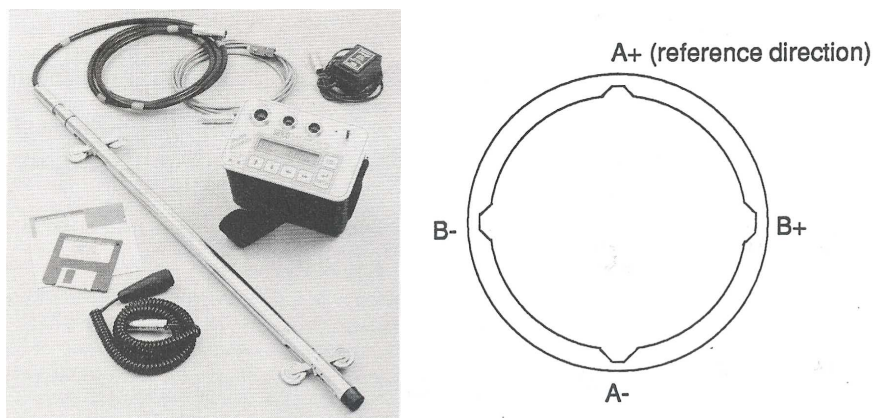


Figure 1.3.1.4: Inclinator equipment is shown (left), alongside a schematic representation of the inclinometer tube (right).

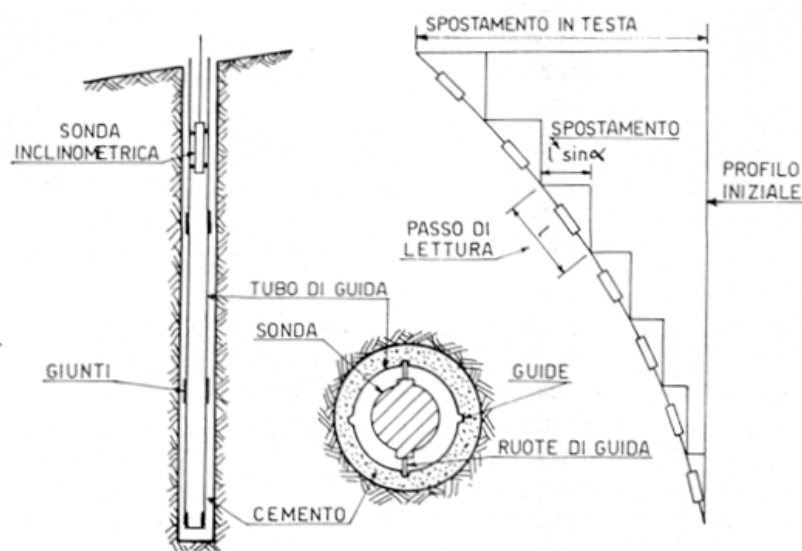


Figure 1.3.1.5: Schematic of an inclinometer borehole showing the inclinometer probe, guide tube, and the measurement procedure for detecting lateral deformations.

Several factors influence the quality of inclinometer measurements, including:

- probe characteristics;
- measurement range;
- sensitivity;
- precision and stability;
- correct installation of the casing;
- casing torsion;
- cleanliness of the casing interior;

- measurement procedures;
- sensor calibration;
- accuracy of the zero reading;
- spacing of measurement points along the vertical;
- frequency of data acquisition;
- repeatability of probe positioning at the same depth;
- operator experience and technical expertise.

It should also be noted that aluminium casings are more deformable than PVC casings, and such deformations may affect recorded data. Furthermore, inclinometer measurements can be subject to both systematic and random errors, arising from borehole drilling, casing installation, measurement execution, and data processing.

Surface Deformations

For the geotechnical monitoring of surface deformations, the most commonly employed instruments are extensometers (wire or rod type), distometers, and crack meters. These devices are primarily used to measure the opening of fractures affecting soil or rock masses.

Extensometers (Fig. 1.3.1.6) are installed to detect variations in the distance between two points located within the landslide area. They are typically applied across fractures or cracks in rock masses, along scarps, or within the crown zone. These instruments usually acquire data automatically and can trigger alarms when predefined thresholds are exceeded.

Distometers, either fixed or removable, may also be used. In both cases, they measure changes in distance between pairs of points. The instruments are anchored to two stable points located across a fracture and connected by a cable that is free to slide along a guide track. When one of the two points moves, the cable shifts accordingly, and using a graduated wire it is possible to determine the magnitude of displacement with precision.

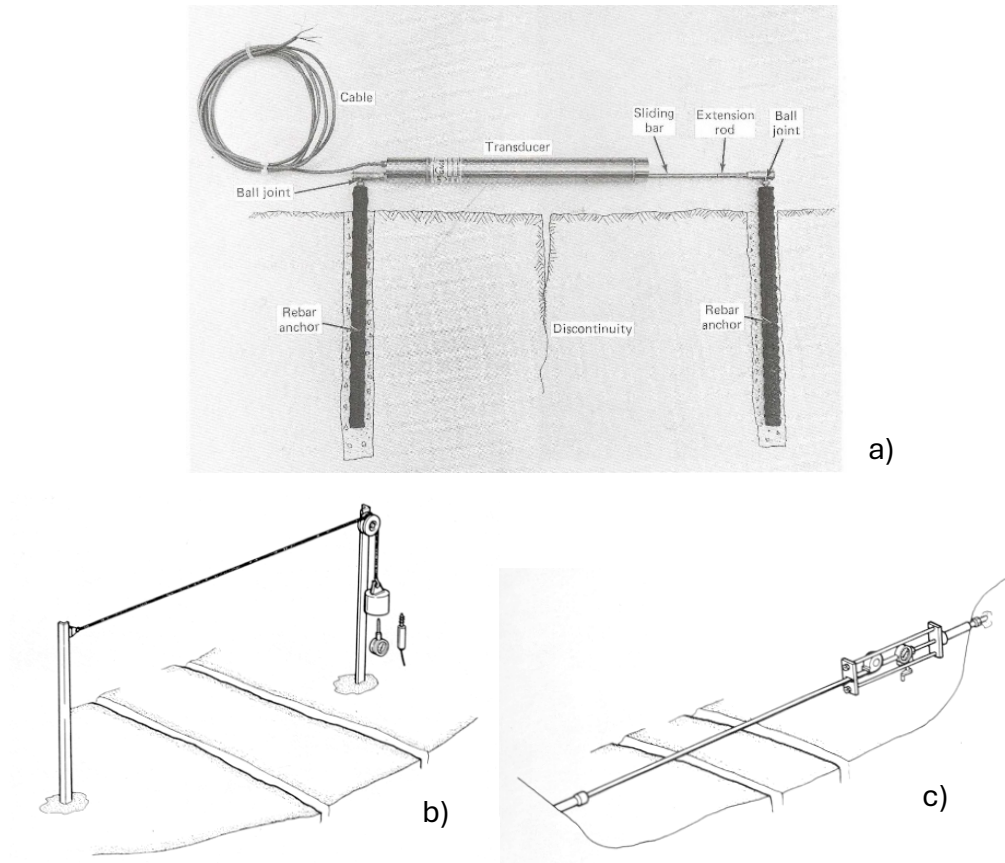


Figure 1.3.1.6: a) Extensometric equipment; b) Schematic representation of a wire extensometer; c) Schematic illustration of the use of a distometer.

1.3.2 Remote Sensing Techniques

Remote sensing techniques include the set of instruments and interpretative methods that extend the perceptual capacity of the human eye, providing both qualitative and quantitative information on objects located at a distance from the observation point. Sensors can be mounted on satellites, drones, aircraft, or terrestrial platforms, with distances ranging from a few meters (proximal sensing) to several thousand kilometers (remote sensing). These techniques allow the investigation of a phenomenon through sensors operating at different wavelengths, by recording the reflected or emitted energy and subsequently processing, analyzing, and interpreting the data.

They are widely applied in the study of surface deformations induced by subsidence, sinkholes, earthquakes, and landslides, whether intermittent or slow. In particular, they are especially suitable for monitoring landslides classified as extremely slow or slow, and for movement types such as slides, flows, lateral spreads, and complex landslides, according to the definition by Cruden and Varnes, 1996.

Remote sensing techniques can be divided into two main categories:

- Optical - passive → record natural radiation (reflected sunlight or emitted radiation).
- Active → the sensor emits a signal (radar, laser) and records the response.

Photogrammetry

Photogrammetry, which belongs to the optical–passive techniques of remote sensing, has been widely used in deformation studies (Ferrero et al., 2004; Mills et al., 2005; Hu et al., 2008; Shao-tang & Zhi-wu, 2008; Smith et al., 2009). The result obtained through this survey technique is a three-dimensional point cloud, which consists of a high-resolution dataset generally made up of millions of points defined by X, Y, and Z coordinates. Ultimately, this technique reconstructs shape, size, and position of objects or surfaces from photographic

images acquired from different angles. It is based on the principle of stereoscopy: by comparing two or more images of the same area taken from different viewpoints, a three-dimensional reconstruction can be obtained.

Photogrammetry can be divided into three types:

- Aerial photogrammetry (Fig. 1.3.2.1a): acquired with drones or aircraft. It provides orthophotos and digital terrain models (DTM) or digital surface models (DSM).
- Satellite photogrammetry (Fig. 1.3.2.1b): acquired from high-resolution optical satellites, which offer large-area coverage and are used for multitemporal analyses.
- Terrestrial photogrammetry (Fig. 1.3.2.1c): acquired with cameras placed on tripods, employed to monitor fractures, rock faces, or small displacements.

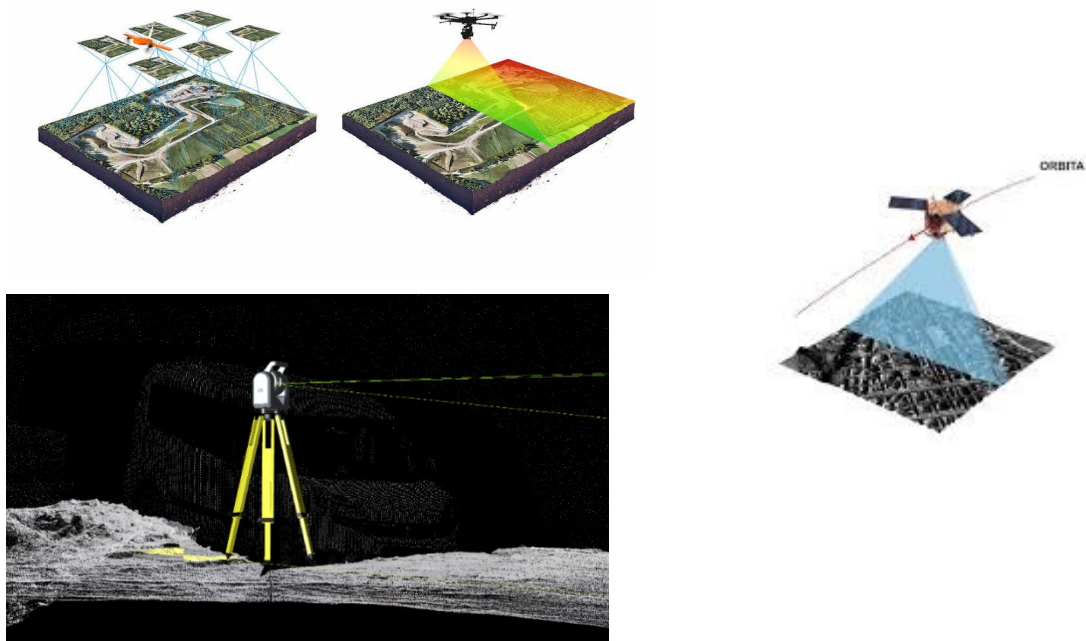


Figure 1.3.2.1: a) Aerial photogrammetry; b) Satellite photogrammetry; c) Terrestrial photogrammetry.

The main advantages of using photogrammetry are the reduction of fieldwork time, the ability to obtain three-dimensional coordinates simultaneously, and, in

theory, the possibility of monitoring an unlimited number of points. In recent years, the accuracy in the determination of photogrammetric point positions has significantly improved, making this technique particularly attractive for high-precision deformation measurements.

The interpretation of aerial photographs has proven to be an effective technique for the recognition and delineation of landslides (Soeters & van Westen, 1996). It allows the recognition and definition of a three-dimensional view of the terrain, from which relationships between morphology, drainage, surface cover, geological materials, and anthropogenic activity can be observed and evaluated. A comprehensive perspective of a wide area and the boundaries of existing landslides can be easily delineated from aerial photographs. Surface and subsurface drainage channels can be mapped, and important relationships between drainage, topography, and other natural or anthropogenic features — which are rarely correctly correlated in the field — become evident in the photographs. Moreover, soils and rock formations can be observed and assessed in their natural state. Recent photographs can be compared with older ones to examine the progressive development of landslides, and aerial photographs can be studied at any time, in any place, and by anyone. Terrestrial photogrammetry and ground-based photography are also used for the monitoring of landslides at the local scale. Sites that are too steep or too small to be observed from the air are suitable for ground-based studies, even at a distance. Terrestrial photogrammetry can be effectively employed in hazardous or inaccessible areas, such as road cuts and active landslides.

In conclusion, this technique presents the following advantages: large areal coverage, high level of detail, repeatability of measurements and multitemporal comparison, cost-effectiveness (especially when carried out with drones), non-invasiveness, and no physical contact with the landslide. Its limitations lie in the dependence on light and weather conditions (clouds, shadows, rain), the need for ground control points (GCPs) to guarantee metric accuracy, the concealment of the ground by vegetation, and reduced accuracy in detecting millimetric

displacements. In landslide monitoring applications, photogrammetry is particularly useful for landslide mapping, with the identification of boundaries and morphologies. It enables volumetric analysis with the calculation of mobilized material volume and is effective in multitemporal monitoring by comparing 3D models acquired at different dates to estimate surface displacements.

Laser scanner - LiDAR

The Terrestrial Laser Scanner (TLS), in its ground-based configuration, or LIDAR, in its airborne configuration, falls under active remote sensing techniques. TLS, deployed on the ground or mounted on terrestrial vehicles, is commonly used for monitoring slopes, active landslides, rock faces, and buildings. Airborne LIDAR, obtained by mounting a scanner on an aircraft or drone, enables broader area coverage, including beneath vegetation, although its accuracy is slightly lower than that of TLS.

The laser scanner measures the three-dimensional coordinates of points on a surface by emitting a laser beam and recording the time taken for the signal to return to the sensor (time-of-flight principle) or by measuring the signal phase. The output consists of high-density point clouds, which can be processed into digital surface models (DSM/DTM), three-dimensional meshes, or orthophotos.

Synthetic Aperture Radar (SAR)

Among the most promising remote sensing techniques are those based on Synthetic Aperture Radar (SAR), which can provide both qualitative and quantitative information on ground and structural deformations, with resolutions ranging from meters to millimeters. Radar technology (Radio Detection and Ranging) uses the emission and reception of electromagnetic waves in the microwave band. Unlike optical sensors, radar systems can operate independently of illumination and weather conditions.

A SAR sensor measures the backscattered electromagnetic field from the terrain, generated by the antenna itself. This feature makes the system

independent of external light sources (e.g., the sun, in the case of optical sensors) and minimally dependent on weather conditions.

SAR systems employ signal processing to “synthesize” a large antenna by exploiting the motion of the platform, achieving high spatial resolution with physically compact antennas. SAR sensors can operate in various spectral bands (L, C, X, etc.), depending on the desired penetration through vegetation or soil. Table 1.3.2.1 reports the wavelengths commonly adopted by SAR sensors.

Table 1.3.2.1: Most used SAR sensors with their bands, frequencies (GHz), and wavelengths (cm).

Band	Frequency (GHz)	Wavelength (cm)	Satellite
P-band	0,225 – 0,39	140 – 76,90	AIRSAR
L-band	0,39 – 1,55	76,90 – 19,30	JERS-1, SAR, ALOS PALSAR
S-band	1,55 – 4,00	19,30 – 7,50	Almaz-1
C-band	4,00 – 8,00	7,50 – 3,75	ERS-1/2 SAR, RADARSAT-1/2, ENVISAT ASAR, RISAT-1
X-band	8,00 – 10,9	3,75 – 2,75	TerraSAR-X-1, COSMO-Skymed
K-band	10,90 – 36	2,75 – 0,83	Military domain/GBSAR

SAR technology also offers different acquisition modes (Fig. 1.3.2.2), balancing resolution and coverage according to the application:

- Stripmap: fixed antenna relative to the flight line; useful for mapping large areas with lower resolution.
- ScanSAR: antenna oriented to illuminate multiple sub-areas; enables wide coverage at the expense of resolution.
- Spotlight: antenna focused on a specific area; provides high-resolution data and allows multiple-angle observations in a single pass.

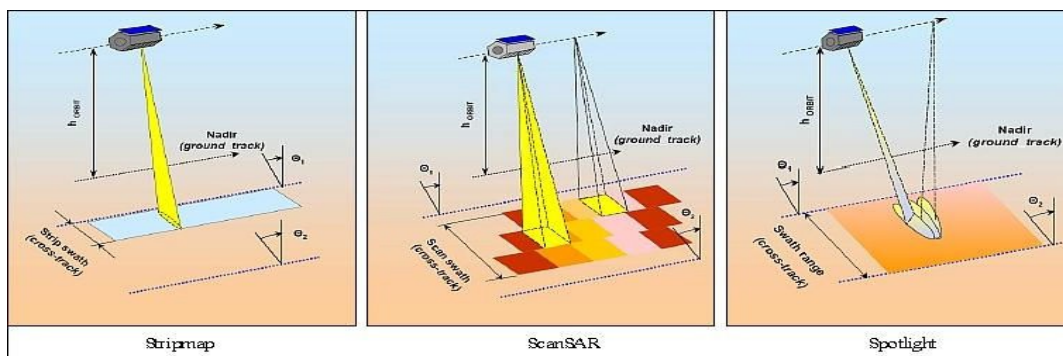


Figure 1.3.2.2: SAR acquisition modes (Stripmap, ScanSAR, Spotlight)

The reference system of a SAR image is defined by range-azimuth coordinates. Since the radar observes laterally, topographic relief produces geometric distortions in the image. These effects can be mitigated using images acquired from multiple angles and digital elevation models (DEM). The main geometric distortions are:

- **Foreshortening:** occurs when the radar beam reaches the base of a slope inclined toward the radar before the top, compressing the slope in the image (Fig. 1.3.2.3a).
- **Layover:** occurs when the beam reaches the top before the base; the top appears projected toward the radar and “falls” onto the base (Fig. 1.3.2.3b).
- **Shadowing:** occurs when terrain areas are not illuminated, with shadows increasing as the incidence angle increases (Fig. 1.3.2.3c).

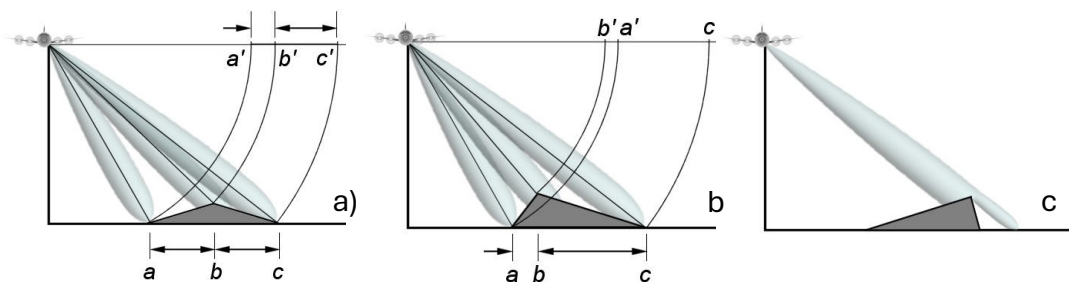


Figure 1.3.2.3: Main geometric distortions affecting a SAR image.

SAR images may also exhibit radiometric distortions, often correlated with geometric distortions, depending on the energy received by the sensor. For instance, a foreshortened slope concentrates energy into a smaller area, producing very bright pixels. In amplitude images, scene structures are distinguishable, although speckle is present, whereas phase images are crucial for interferometric analyses.

Speckle arises from interference between waves backscattered by different objects within a pixel, amplifying or attenuating the signal. Its intensity depends on the frequency band, scattering properties of the targets, and incidence angle. Speckle can be reduced using multilook processing and spatial filters (Lee,

Frost, Gamma, Kuan). Multilook processing subdivides radar returns into shorter intervals and averages them, reducing noise and spatial resolution.

The first SAR satellite was SeaSat-1 (1978), designed for ocean observation. Later systems include SIR-C/X-SAR (1994) and SRTM/X-SAR (2000), the latter producing DEMs and topographic products. The main operational SAR missions are summarized in Table 1.3.2.2.

SAR interferometry (InSAR) was first described by Gabriel et al. (1989). The development of multipass interferometric techniques (Berardino et al., 2002; Ferretti et al., 2002) has enabled highly accurate quantitative monitoring of deformations along the Line of Sight (LOS). InSAR relies on analyzing the phase differences between two SAR images acquired from different spatial positions. The phase difference, when properly processed and compared with the terrain topography, allows the generation of high-resolution digital elevation models (DEMs) and deformation maps with millimeter-level accuracy.

SAR images can be acquired from ascending or descending orbits, corresponding to illumination from west or east, respectively. Combining these datasets reduces many geometric distortions and allows estimation primarily of East-West and vertical motion components, while the North-South component is generally neglected.

Operationally, the key information is contained in the interferogram, which is obtained by multiplying a reference image (master) by the complex conjugate of a second image (slave). The amplitude of the resulting signal corresponds to the product of the amplitudes of the two images, while the phase represents the pixel-by-pixel phase difference, from which topographic and displacement information can be derived.

The geometric parameters of acquisition are fundamental in interferometric analysis (Fig. 1.3.2.4). The distance between the two satellites on the plane perpendicular to the orbital direction is called the interferometric baseline (B_r), and its component perpendicular to the line of sight (slant range) is referred to as the perpendicular baseline (B_n).

Table 1.3.2.2: Major SAR Satellite Missions

Satellite / Mission	Launch Year	Operational Period	SAR Band	Main Objectives / Notes
SeaSat-1	1978	Short-term	L	Ocean observation and study
SIR-C/X-SAR	1994	Short-term	L, C, X	Coverage of 230 test sites during two seasonal periods
SRTM/X-SAR	2000	Short-term	C, X	DEM and topographic product generation
ERS-1	1991	1991–2000	C	First ESA operational Earth observation mission
ERS-2	1995	1995–2011	C	Additional ozone sensor, Earth observation
JERS-1	1992	1992–??	L	Territory, agriculture, forestry, fishing, coastal monitoring
RADARSAT-1	1995	1995–??	C	Monitoring natural resources and environmental changes
RADARSAT-2	2007	Active	C	High resolution, selectable polarization, left/right images, environmental monitoring
ENVISAT	2002	2002–2012	C	Successor to ERS, multiple instruments including radar, altimeter, radiometer
ALOS	2006	2006–??	L	Cartography, regional monitoring, disaster management, resource detection
TerraSAR-X	2007	2008–??	X	High-resolution mapping, monitoring movements; TanDEM-X (2010)
COSMO-SkyMed	2007–2010	Active	X	Dual-use, environmental monitoring, risk management, commercial services, 4 satellites
Sentinel-1	2014	Active	C	SAR, GMES program, environmental and risk monitoring
Sentinel-2	2015	Active	Optical	High-resolution land observation and emergency monitoring
Sentinel-3	2016	Active	Optical & microwave	Marine and terrestrial operational services

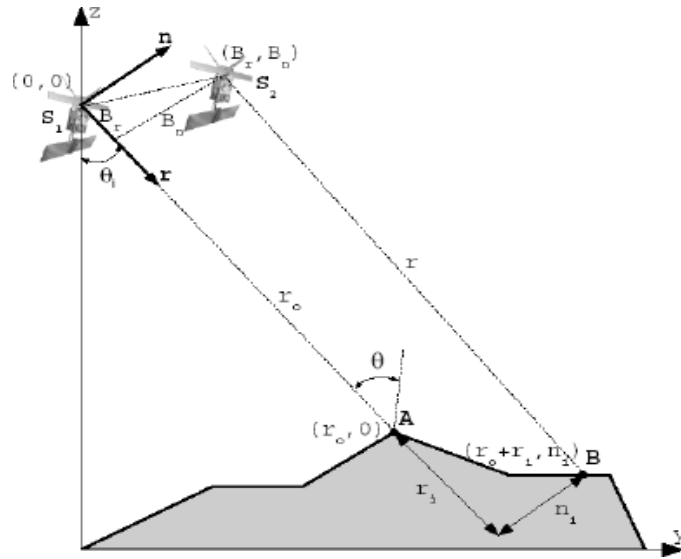


Figure 1.3.2.4: Interferogram acquisition geometry (Blanco, 2008).

InSAR assumes that each area illuminated by the radar has a dominant scatterer observed from two different angles. The difference in path lengths between the signals (Δr) is related to the baseline and produces a phase difference ($\Delta\phi$), which is proportional both to the relative height of the ground points and to the distance along the line of sight. To correct for topographic effects, a reference DEM is used. If the DEM is inaccurate, the resulting interferogram is “flattened” and retains residual topographic signals; if the DEM is accurate, a true displacement map can be derived. Phase discontinuities appear as interferometric fringes, due to the cyclic nature of phase ($\pm 2\pi$). The height corresponding to the difference between two fringes is called the height of ambiguity (ha), which is inversely proportional to B_n . A large perpendicular baseline increases height sensitivity but also increases ambiguities. If the baseline exceeds a critical value, the phase signal becomes noisy. Phase unwrapping is applied to remove $\pm 2\pi$ ambiguities, allowing the interferogram to be converted into a georeferenced SAR elevation map (DEM), referenced to an ellipsoid such as WGS84. This is valuable for a wide range of applications, including urban planning, environmental monitoring, and natural hazard management. Interferometric processing can also detect small relative displacements between points within the same scene. Such deformations may

result from sudden events (e.g., earthquakes), slow natural phenomena (e.g., glacier melting), or human activities (e.g., fluid extraction causing subsidence). In these cases, the interferometric phase ($\Delta\phi$) is supplemented by an additional term (d) related to target displacement, independent of the baseline. Target displacement is projected along the line of sight (slant range); after flattening, the residual phase contains both residual topographic contributions and contributions due to ground deformation.

Using an accurate DEM, the topographic contribution can be removed, isolating the deformations and obtaining a differential interferogram. SAR is extremely sensitive to displacements: a deformation along the line of sight equal to a fraction of the wavelength generates a significant phase shift (2π). The precision of measurements, both in terms of elevation and displacement, depends on several geometric and structural parameters, which vary according to acquisition configuration.

The InSAR technique can be affected by several types of errors:

1. Orbital errors – inaccuracies in the satellite's position and velocity produce geometric errors; very accurate orbital parameters are required to reduce these errors.
2. Atmospheric effects – variations in humidity, temperature, and pressure alter the radar signal propagation speed, introducing phase delays.
3. Noise – primarily due to decorrelation:
 - Temporal decorrelation: caused by rapid changes in scatterers (e.g., vegetation growth).
 - Spatial decorrelation: caused by differences in incidence angle or excessively large baselines (beyond the critical baseline).
 - Volumetric scattering: caused by volumetric distribution of scatterers (e.g., forests), generating multiple signal paths.

1.3.3 Topographic and geodetic techniques

Among topographic and geodetic techniques, we highlight leveling, which allows the determination of elevation changes with millimeter precision, and the total station, which, through distance and angle measurements, can detect both planimetric and altimetric displacements.

By using total stations, the movement of a point on the Earth's surface is measured relative to benchmarks or reference stakes. Since benchmarks must be placed in a stable area outside the landslide, their use is impractical in large landslide-prone areas. Reference stakes, instead, are positioned within the moving zone. In the Figure 1.3.3.1 is shown the instrumentation of a total station.



Figure 1.3.3.1: Total station instrumentation and reflective prisms used for topographic measurements.

By repeating measurements over time, it is possible to obtain the variation of the point's position along all three components. The operational mode can be manual, in the case of periodic surveys, or automated/robotic, when measurements are continuous and remotely monitored. The advantages of this approach lie in the high measurement precision (mm–cm) and in the possibility of monitoring multiple targets simultaneously, even in large landslide areas. The

limitations stem from the point-based nature of the survey and the necessity of a clear line of sight between the instrument and the target, which may be affected by atmospheric conditions (fog, heavy rain).

Three methods can be used to determine the displacement of a point:

1. Triangulation: the position of a point is determined by combining angular and distance measurements from at least two stations;
2. Trilateration: the position of a point is determined using distance measurements from at least three stations;
3. Triangulation: the position of a point is determined using both distance and angular position relative to a station.

In Figure 1.3.3.2, the magnitude of errors for measurements using triangulation, trilateration, and triangulation is shown as a function of the distance from the control point (Ashkenazi & Cross, 1976a).

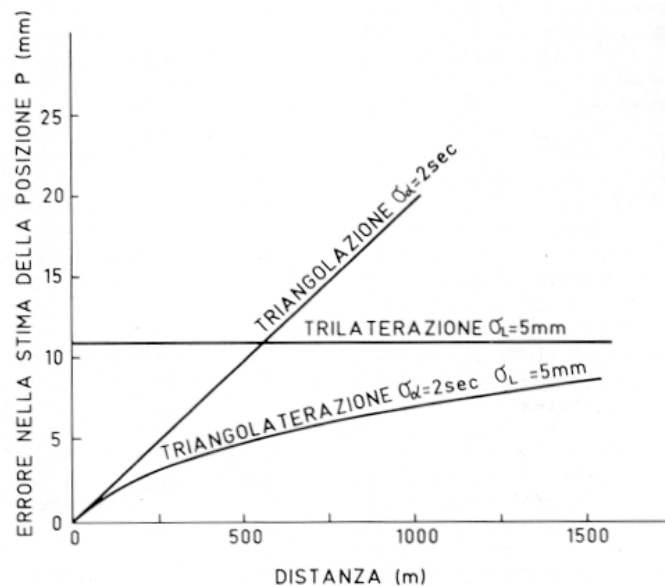


Figure 1.3.3.2: As the distance of the point from the reference station increases, the error increases for triangulation and triangulation, while it remains constant for trilateration (Ashkenazi & Cross, 1976b).

The reliability of the measurement is expressed as the error in position estimation, whereas the sensitivity and accuracy of the instrument depend on the stability of the topographic station, movements of the surface layer, and atmospheric conditions.

Global Navigation Satellite Systems - GNSS

Global Navigation Satellite Systems (GNSS) have revolutionized the way positioning and navigation are performed on Earth, transforming both civilian and military applications. The introduction of these systems marked a decisive shift from traditional terrestrial methods to satellite-based positioning, enabling unprecedented levels of accuracy, global coverage, and reliability. The first operational system was the Global Positioning System (GPS), developed and deployed by the U.S. Department of Defense in the 1970s. Initially conceived as a secure, high-accuracy positioning system for military purposes, GPS incorporated advanced features to protect signals from jamming and interference. Nevertheless, shortly after achieving initial operational capability in December 1993, the system was extended to civilian users. This expansion rapidly spurred the development of applications across diverse domains, including surveying, mapping, aviation, maritime navigation, and land transportation. Civilian requirements, however, often differ from military needs, particularly in terms of service availability, accuracy, and cost-effectiveness.

GNSS constellations

The acronym GNSS (Fig. 1.3.3.3) is now used to denote the entire ensemble of global and regional satellite navigation systems that are either operational or under development. These include, in addition to GPS, other major constellations such as Russia's GLONASS, Europe's Galileo, China's BeiDou, as well as regional systems like India's NavIC (IRNSS) and Japan's QZSS. The coexistence and interoperability of these systems ensure improved availability, redundancy, and positioning accuracy worldwide.

GPS (USA) – The Global Positioning System (GPS)—formally known as NAVSTAR GPS (NAVigation System with Time And Ranging Global Positioning System) - was the pioneering satellite navigation system. Developed by the U.S. Department of Defense in the late 1970s, GPS was designed to provide global, all-weather, high-accuracy positioning capabilities. The system

employs a constellation of 27 satellites (24 operational plus spares) orbiting the Earth in medium Earth orbit (MEO) at an altitude of approximately 20,200 km. These satellites are distributed across six orbital planes, ensuring continuous global coverage. Since its inception, GPS has become the backbone of modern navigation and continues to undergo modernization, including the introduction of new signals (e.g., L2C, L5) and next-generation satellites with enhanced accuracy and resilience.

GLONASS (Russia) – The Global Navigation Satellite System (GLONASS) was initiated by the Soviet Union in the 1970s as a strategic counterpart to the U.S. GPS. Originally conceived as an experimental military communication and navigation system, the first GLONASS satellite was launched in 1982. By 1993, the constellation was declared fully operational. Today, GLONASS comprises 24 operational satellites in MEO, orbiting at approximately 19,100 km. The system provides global coverage and has undergone significant modernization, including the deployment of GLONASS-M and GLONASS-K satellites with extended lifetimes and additional signal capabilities.

Galileo (European Union) – Galileo represents the European Union's contribution to global satellite navigation. Unlike GPS and GLONASS, Galileo is a civilian-controlled system, designed to provide high-accuracy positioning services independently of military control. Development began in the early 2000s, with the first experimental satellite (the Galileo System Test Bed, GSTB) launched in 2005. Validation of the system began with four In-Orbit Validation (IOV) satellites launched between 2011 and 2012. Full Operational Capability (FOC) satellites followed in 2014, progressively expanding the constellation. Galileo is planned to consist of 27 operational satellites plus spares, orbiting at an altitude of about 23,000 km. It offers a range of services, including the Open Service (OS) for civilian users, the Commercial Service (CS) with enhanced accuracy, and the Public Regulated Service (PRS) for governmental and emergency applications.

BeiDou (China) – The BeiDou Navigation Satellite System (BDS) has been developed in phases by China, evolving from a regional to a global service. The first phase, BeiDou-1, provided regional coverage using a limited constellation. The second phase, BeiDou-2 (Compass), extended coverage to the Asia-Pacific region and became operational in December 2012. The third phase, BeiDou-3, achieved global coverage in 2020 with a constellation of 35 satellites: 27 in MEO, 5 in geostationary orbit (GEO), and 3 in inclined geosynchronous orbits (IGSO). BeiDou offers multiple services, including open positioning, timing, and short message communication, making it unique among GNSS constellations.

IRNSS (India) – The Indian Regional Navigation Satellite System (IRNSS), also known as NavIC (Navigation with Indian Constellation), is a regional GNSS developed and operated by the Indian Space Research Organisation (ISRO). Unlike global systems, NavIC provides positioning services over India and up to 1,500 km beyond its borders. The constellation consists of 7 satellites: 3 in GEO and 4 in IGSO, fully operational since 2015. NavIC provides two levels of service: the Standard Positioning Service (SPS), available to all users, and the Restricted Service (RS), an encrypted service for authorized users such as the military.

QZSS (Japan) – The Quasi-Zenith Satellite System (QZSS) is a regional augmentation system developed by Japan to enhance GNSS performance over the Asia-Oceania region. The system currently consists of 4 satellites, primarily operating in inclined geosynchronous orbits that allow at least one satellite to always remain near the zenith over Japan.

QZSS is designed to work in conjunction with GPS, transmitting on compatible frequencies and time references. While QZSS alone provides limited accuracy, its integration with GPS significantly improves positioning performance in urban environments and areas with challenging satellite visibility.

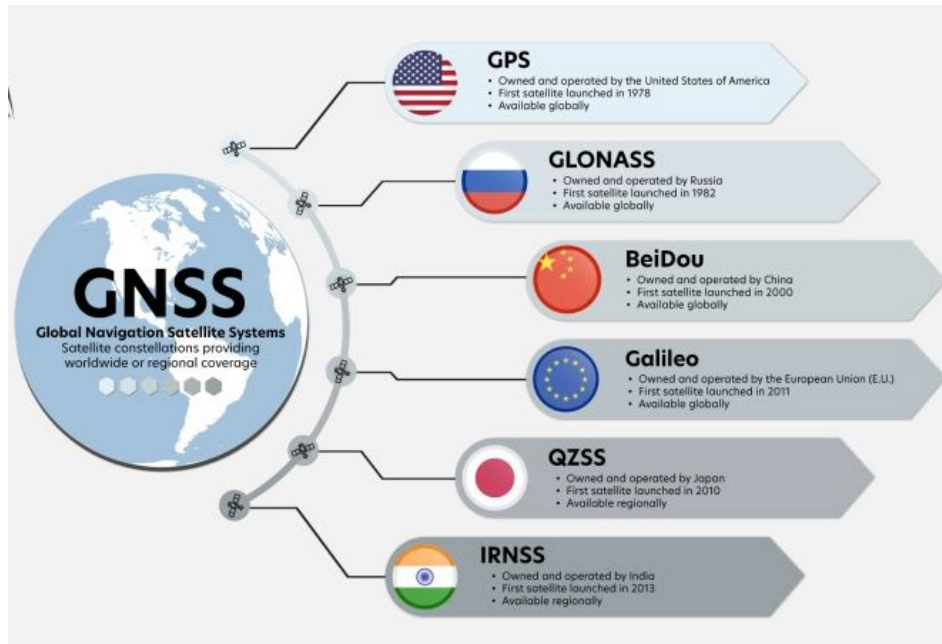


Figure 1.3.3.3: Main Global Navigation Satellite Systems (GNSS): GPS (USA), GLONASS (Russia), BeiDou (China), Galileo (EU), QZSS (Japan), and IRNSS (India), with their operators, launch dates, and coverage (GPS Overview Part 1: What is GPS and GNSS Positioning?, s.d.).

GNSS architecture

A Global Navigation Satellite System (GNSS) is composed of three main segments: the space segment, the ground (or control) segment, and the user segment (Fig. 1.3.3.4).

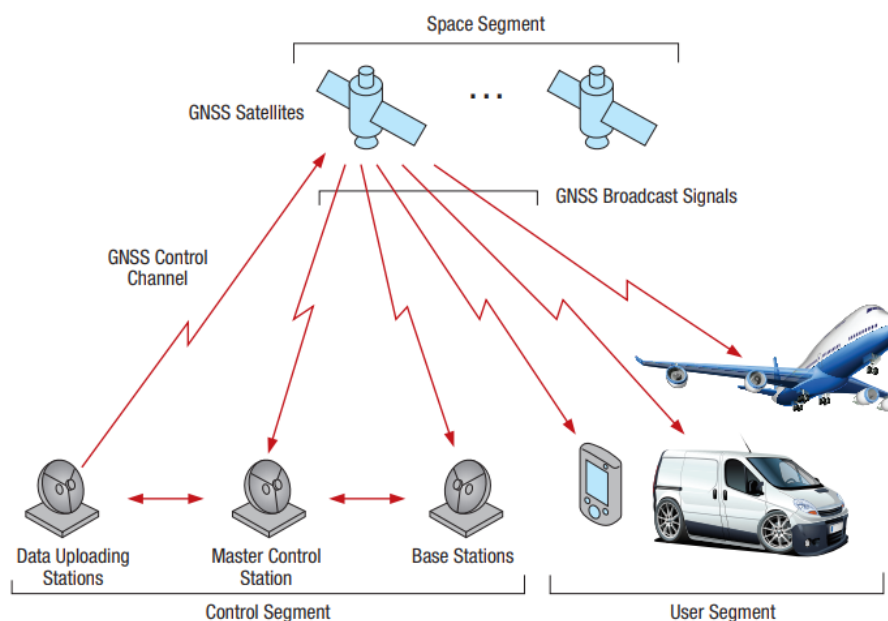


Figure 1.3.3.4: Simplified architecture of the Global Navigation Satellite System (GNSS), illustrating the three main segments: space, control, and user (Jeffrey, 2010).

These components work together to ensure the accurate and reliable delivery of positioning, navigation, and timing (PNT) services across the globe.

Space Segment: The space segment is the most visible component of GNSS and consists of the constellation of navigation satellites orbiting in medium Earth orbit (MEO). Each satellite continuously broadcasts signals containing orbital parameters (ephemeris data), clock correction data, almanac data, navigation messages, which may also include information about ionospheric conditions, system health, and additional correction data. The space segment ensures global signal coverage, providing redundancy through multiple satellites visible from any point on Earth. Typically, a GNSS constellation is designed so that at least four satellites are simultaneously visible to users, a requirement for three-dimensional positioning and time determination.

Control Segment: The ground segment monitors and manages the performance of the satellite constellation. It comprises a global network of monitoring stations, master control centers, and uplink facilities. Its primary responsibilities include: tracking satellites to determine their orbits and health status; synchronizing and maintaining satellite clocks, ensuring that timing errors are minimized; calculating precise orbital and clock correction data, which are uploaded to the satellites for broadcast; command and control operations, such as repositioning satellites, uploading software updates, or decommissioning aging spacecraft.

For example, the U.S. GPS control segment includes monitoring stations strategically distributed worldwide, a Master Control Station (MCS) that processes tracking data and computes corrections, and ground antennas that uplink commands and updated navigation data to the satellites. Other GNSS constellations maintain similar infrastructures, adapted to their regional or global coverage goals.

User Segment: The user segment consists of receivers that capture and process GNSS satellite signals to compute and utilize position, velocity, and time information. These receivers range from mass-market devices, such as

smartphones and handheld navigation units, to highly specialized equipment used for advanced surveying, geodesy, and scientific applications.

GNSS positioning

The principle underlying GNSS positioning is known as trilateration. If the position of a receiver is unknown, but its distance from three reference points is known, its location can be determined geometrically (Fig. 1.3.3.5). For instance, if the receiver is 3 km from Point A, it must lie somewhere on the circumference of a circle with radius 3 km centered at Point A. If the distance to a second reference point, Point B, is also known (e.g., 4 km), the possible positions are reduced to two, corresponding to the intersections of the two circles.

By introducing a third measurement, for example 6 km from Point C, the ambiguity is resolved, since only one physical point satisfies all three distance constraints.

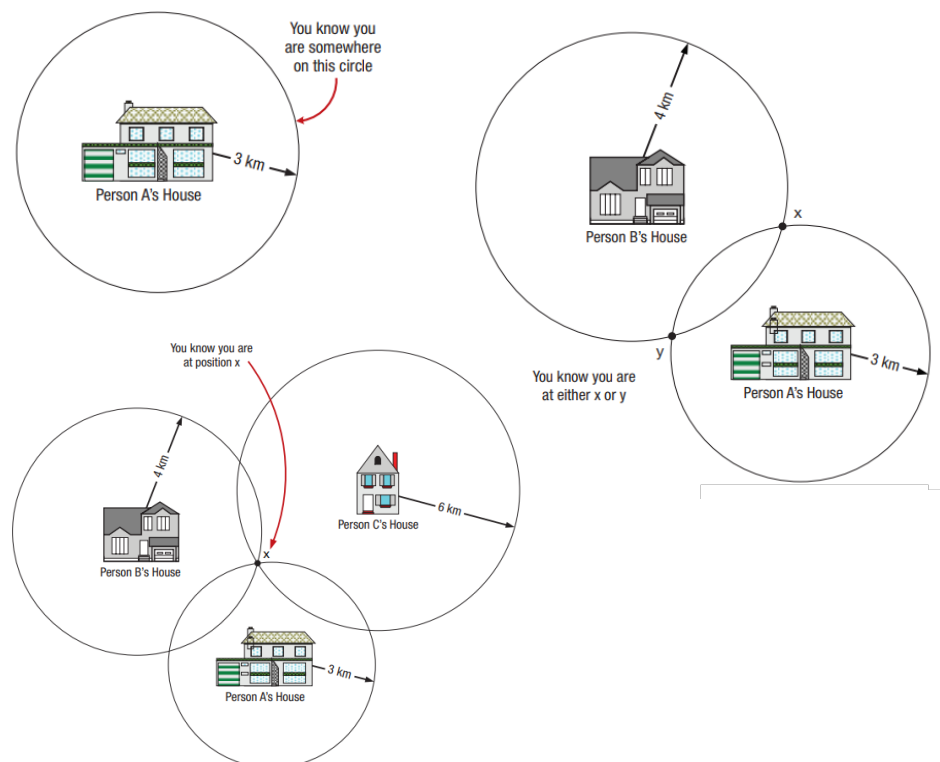


Figure 1.3.3.5: Illustration of the trilateration principle: the intersection of circles, representing known distances from three reference points (Person A, B, and C's houses), determines the precise location of an unknown point (Jeffrey, 2010).

In the case of GNSS, the reference points are not houses but satellites. Furthermore, in practice, a minimum of four satellites is required, in order to determine the three-dimensional position (latitude, longitude, and altitude) and to correct the receiver clock offset.

The technique involves a series of steps (Fig. 1.3.3.6) to determine time and position:

STEP 1 - SATELLITES: GNSS satellites orbit the earth. The satellites know their orbit ephemerides (the parameters that define their orbit) and the time very, very accurately. Ground-based control stations adjust the satellites' ephemerides and time, when necessary.

STEP 2 - PROPAGATION: GNSS satellites regularly broadcast their ephemerides and time, as well as their status. GNSS radio signals pass through layers of the atmosphere to the user equipment.

STEP 3 - RECEPTION: GNSS user equipment receives the signals from multiple GNSS satellites then, for each satellite, recovers the information that was transmitted and determines the time of propagation, the time it takes the signals to travel from the satellite to the receiver.

STEP 4 - COMPUTATION: GNSS user equipment uses the recovered information to compute time and position.

STEP 5 - APPLICATION: GNSS user equipment provides the computed position and time to the end user application, for example, navigation, surveying or mapping.

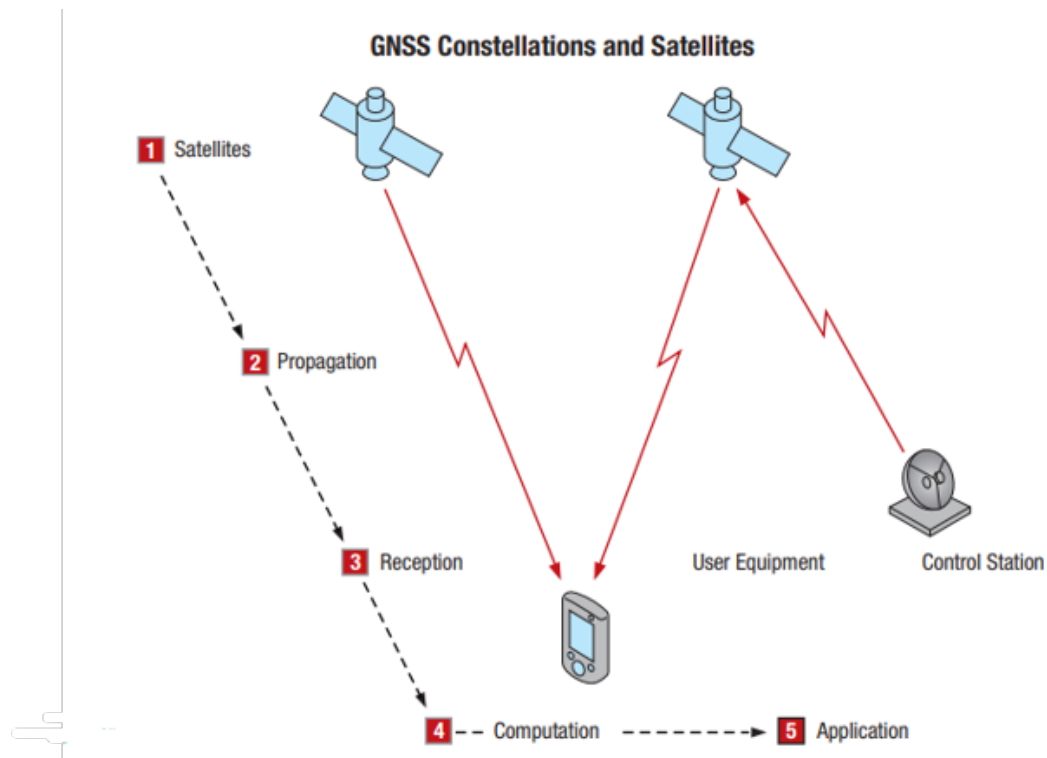


Figure 1.3.3.6: Basic GNSS Operational Framework. Depicts the signal flow and core components of a GNSS, from the 1 Satellites to 2 Propagation, 3 Reception, 4 Computation, and 5 ultimate Application. The system relies on both User Equipment and dedicated Control Stations for proper functioning (Jeffrey, 2010).

STEP 1 – SATELLITES

GNSS satellites orbit well above the atmosphere, in medium Earth orbits (MEO), which are nearly circular, highly stable, and predictable. GPS and GLONASS satellites orbit at altitudes of about 20,000 km, while BeiDou and Galileo operate slightly higher, around 21,500 km and 23,000 km respectively. At such altitudes atmospheric drag is negligible, but gravitational perturbations and solar radiation pressure still affect the trajectories, requiring occasional orbit corrections. During these maneuvers, satellites are flagged as “out of service” so that receivers exclude their signals.

Moving at several kilometres per second, GNSS satellites follow highly predictable paths in the vacuum of space. They carry extremely precise clocks and broadcast their orbital ephemerides with great accuracy. The latest GPS satellites, for instance, use rubidium atomic clocks accurate to ± 5 parts in 10^{11} ,

synchronized with even more stable ground-based cesium standards—so precise that a cesium clock would take over 100,000 years to drift by one second. Clearly, equipping every GNSS receiver with such clocks would be impractical, which is why timing is maintained in orbit.

Time accuracy is crucial because GNSS ranging relies on measuring the travel time of signals between satellites and receivers. Since radio waves propagate at the speed of light, even tiny timing errors produce large positional errors: in one microsecond light travels 300 m, and in a single nanosecond about 30 cm.

Access to multiple GNSS constellations benefits end users by improving redundancy and availability. In case of failure in one system, compatible receivers can switch to others. More commonly, signals from several constellations are combined to mitigate blockages, which frequently occur in urban environments or areas with dense vegetation.

Satellite signals

GNSS satellite signals are inherently complex, and their description requires the use of technical concepts such as pseudorandom sequences, correlation, and Code Division Multiple Access (CDMA). Frequency plans, which define the frequencies, amplitudes, and bandwidths of the signals, differ slightly among the various constellations while maintaining a similar conceptual structure.

GNSS radio signals operate at frequencies around 1.5 GHz, within the so-called L-band of the radio spectrum (1–2 GHz). These frequencies are higher than those used for FM broadcasting but lower than those typical of microwave devices. A key characteristic is that, by the time they reach the Earth's surface, GNSS signals are extremely weak, which necessitates the use of advanced acquisition and tracking techniques.

In the case of the GPS system, the principal frequencies are L1, L2, and L5, which can be shared among all satellites thanks to the CDMA transmission scheme. Under CDMA, each satellite transmits on the same carrier frequency but modulates the signal with a unique pseudorandom digital sequence.

Although these codes appear random, they repeat cyclically after a fixed interval and are pre-stored in the receivers. Correlation with the appropriate code enables the receiver to isolate the signal of an individual satellite from both background noise and the signals of other satellites, thereby ensuring proper decoding.

On the L1 frequency, GPS transmits a low-bit rate navigation message together with two distinct codes:

- the Coarse/Acquisition (C/A) code, freely accessible and intended for civilian use;
- the Precision (P) code, which, when combined with an anti-spoofing mechanism, becomes the P(Y) code, restricted to authorized users.

The navigation message conveys essential information, including:

- GPS date and time;
- satellite operational status and health, including notifications of malfunctions or orbit maintenance, in which case the satellite is flagged as “out of service”;
- ephemeris data, which allow the receiver to compute the precise position of the satellite at the epoch of transmission;
- the almanac, a dataset containing coarse orbital and status information for the entire constellation, used by receivers during initialization to identify available satellites for tracking.

The P(Y) code, intended for military applications, provides stronger resistance to interference and jamming, thereby ensuring greater robustness of the military service compared to the civilian one.

The L2 frequency also carries the P(Y) code and, in modern satellites, additionally transmits the L2C signal, a second civilian service designed to enhance accuracy and reliability through dual-frequency measurements. Although the P(Y) code itself remains encrypted and inaccessible, advanced

techniques allow civilian receivers to exploit the L2 carrier for improved ionospheric corrections and positioning accuracy.

The L5 frequency, introduced with the latest generation of GPS satellites, provides an additional civilian signal with higher power, wider bandwidth, and enhanced resistance to interference. These characteristics make L5 particularly suitable for safety-critical applications, such as aviation navigation and advanced transportation systems.

Despite its complexity, the GPS transmission scheme offers several advantages:

- the ability to acquire very weak signals using compact, low-cost antennas;
- compensation of ionospheric delays through multi-frequency operation;
- high resistance to intentional and unintentional interference (*jamming*);
- clear separation between civilian and military services, ensuring higher levels of security.

Other GNSS constellations, such as Galileo, GLONASS, and BeiDou, adopt transmission principles conceptually similar to GPS, relying on pseudorandom codes and shared frequency bands among multiple satellites. However, each system exhibits specific differences in frequency allocations, coding structures, and service provisions, which will be examined in detail in the following sections.

STEP 2 – SIGNAL PROPAGATION

After transmission, GNSS signals travel through the near-vacuum of space and subsequently traverse the Earth's atmosphere before reaching the receiver. Accurate positioning and timing require knowledge of the geometric path length between the satellite and the user equipment, referred to as the range. In practice, however, the measured range is affected by propagation delays, since electromagnetic waves deviate from a straight-line trajectory when passing through media of varying refractive index.

The distance to the satellite is obtained by multiplying the signal propagation time by the speed of light. Any error in estimating the propagation time directly affects the computed range. Because these measurements include systematic errors, the resulting values are referred to as pseudoranges, rather than true ranges.

The most significant atmospheric contribution arises from the ionosphere, located approximately between 70 and 1,000 km above the Earth's surface. The free electrons in this region affect the phase velocity of radio waves, introducing a delay that is frequency dependent. Dual-frequency measurements (e.g., using GPS L1 and L2 signals) enable receivers to effectively eliminate the first-order ionospheric delay by exploiting this frequency dependence.

The troposphere, the lowest layer of the atmosphere, also introduces signal delays. Unlike the ionosphere, tropospheric delay is non-dispersive in the L-band; thus, both L1 and L2 frequencies are equally affected. Tropospheric delay depends on local meteorological conditions such as temperature, pressure, and relative humidity. Although it cannot be removed through dual-frequency techniques, it can be modeled and partially compensated for using empirical or physical models.

A further source of error is multipath propagation, which occurs when part of the signal energy is reflected by surfaces before reaching the receiver antenna. Reflected signals arrive later than the direct signal and, if sufficiently strong, may interfere with it, degrading measurement accuracy. Modern receiver designs incorporate techniques to mitigate multipath by prioritizing the earliest-arriving signal components and suppressing delayed replicas.

Historically, ionospheric and tropospheric delays constituted the dominant error sources in GNSS positioning. With advances in modeling and dual-frequency processing, however, multipath mitigation has become increasingly critical to further enhance system performance. In the Figure 1.3.3.7 is shown the

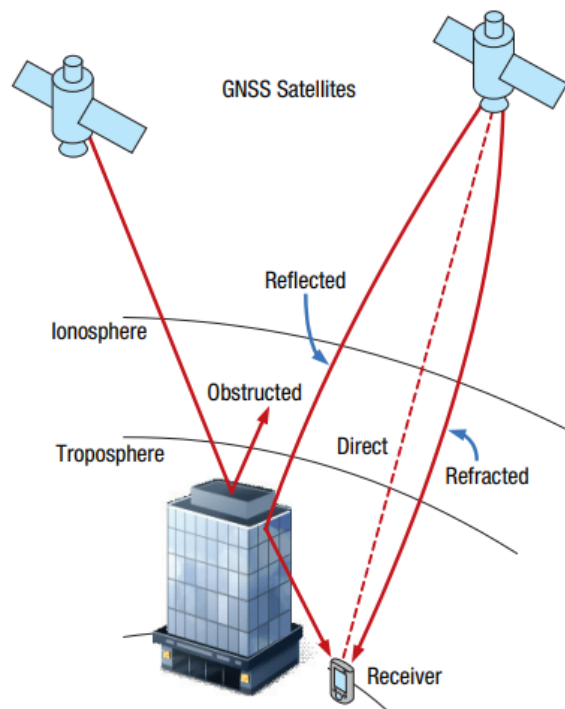


Figure 1.3.3.7: Illustration of Major GNSS Signal Impairments (Jeffrey, 2010).

STEP 3 – SIGNAL RECEPTION

The GNSS signal is captured by the user equipment, which consists of receivers and antennas (Fig. 1.3.3.8). Depending on the application, these components may be physically separated or integrated into a single assembly. GNSS antennas receive the radio signals transmitted by the satellites and forward them to the receivers. They are available in a wide range of shapes, sizes, and performance levels, with the choice of antenna largely depending on the intended application. For example, a large, high-performance antenna may be suitable for a fixed base station, whereas a lightweight, low-profile, aerodynamic antenna is preferable for aircraft or Unmanned Aerial Vehicle (UAV) installations. Receivers process the signals recovered by the antenna to compute position and time. Depending on their design, receivers may use signals from a single GNSS constellation or from multiple constellations simultaneously. They are available in many form factors and configurations, tailored to meet the requirements of diverse GNSS applications.



Figure 1.3.3.8: Example of GNSS instrumentation (Antennas and receiver)

For a three-dimensional position fix and time determination, a GNSS receiver must track signals from at least four satellites. The use of additional satellites, when available, improves the accuracy and robustness of the solution. Modern receivers are capable of acquiring and tracking signals from multiple satellites across different GNSS constellations, thereby enhancing redundancy and availability.

Successful reception requires an unobstructed line of sight between the receiver antenna and the satellites being tracked (Fig. 1.3.3.9). For each satellite, the receiver estimates the signal propagation time by exploiting the pseudorandom nature of the transmitted codes. Since the receiver stores the pseudorandom sequence associated with each satellite, it can align its internally generated replica with the incoming signal. The time offset that maximizes correlation corresponds to the signal travel time, from which the pseudorange is derived.

The number of constellations and satellites a receiver can track simultaneously depends on its design and capabilities. Multi-constellation and multi-frequency receivers provide improved positioning performance, particularly in environments where visibility of satellites is limited.

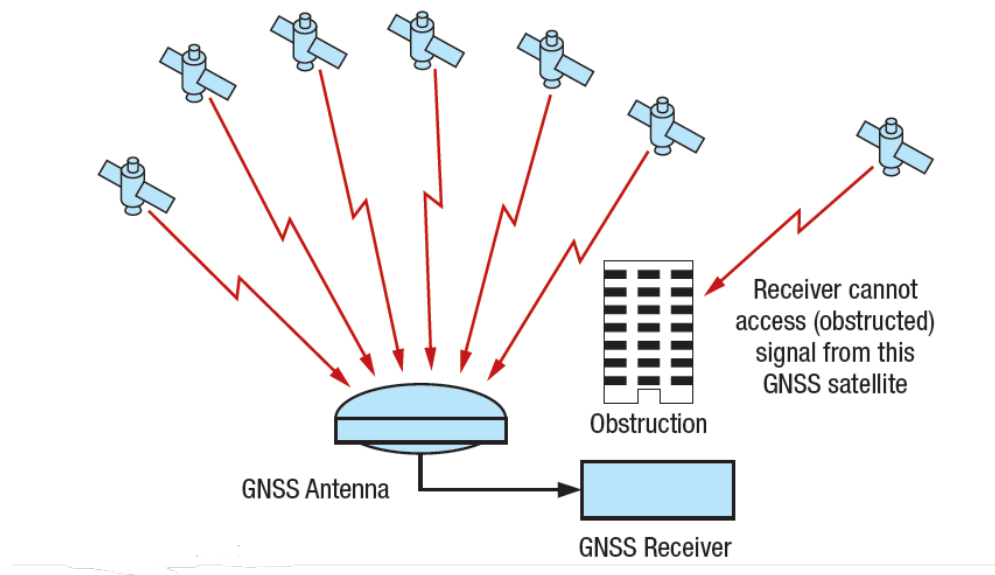


Figure 1.3.3.9: Effect of an Obstruction on GNSS Satellite Availability (Jeffrey, 2010).

STEP 4 – COMPUTATION

In principle, if the exact position of three satellites and the corresponding ranges were known, a receiver could determine its location geometrically through trilateration. In practice, however, at least four satellites are required. This section explains the underlying reason and the computational process involved in GNSS positioning.

For each tracked satellite, the receiver determines the signal propagation time as:

$$\text{Propagation Time} = \text{Time}_{\text{Signal Reached Receiver}} - \text{Time}_{\text{Signal Left Satellite}}$$

Multiplying this propagation time by the speed of light yields the pseudorange to the satellite. Since the satellite continuously broadcasts its orbital ephemerides, the receiver knows the precise position of the satellite at the time of transmission and can thus associate each pseudorange with a known satellite position. The position of the receiver is then determined by trilateration, i.e., finding the common intersection point of the spheres defined by the pseudoranges. To illustrate, consider the two-dimensional case (Fig. 1.3.3.10). The range to a first satellite defines a circle, with the satellite position as its center and the pseudorange as its radius. A second pseudorange defines another

circle, and the receiver must lie at one of their two intersection points. A third pseudorange typically resolves the ambiguity, as one of the solutions is physically implausible (e.g., located in space or within the Earth).

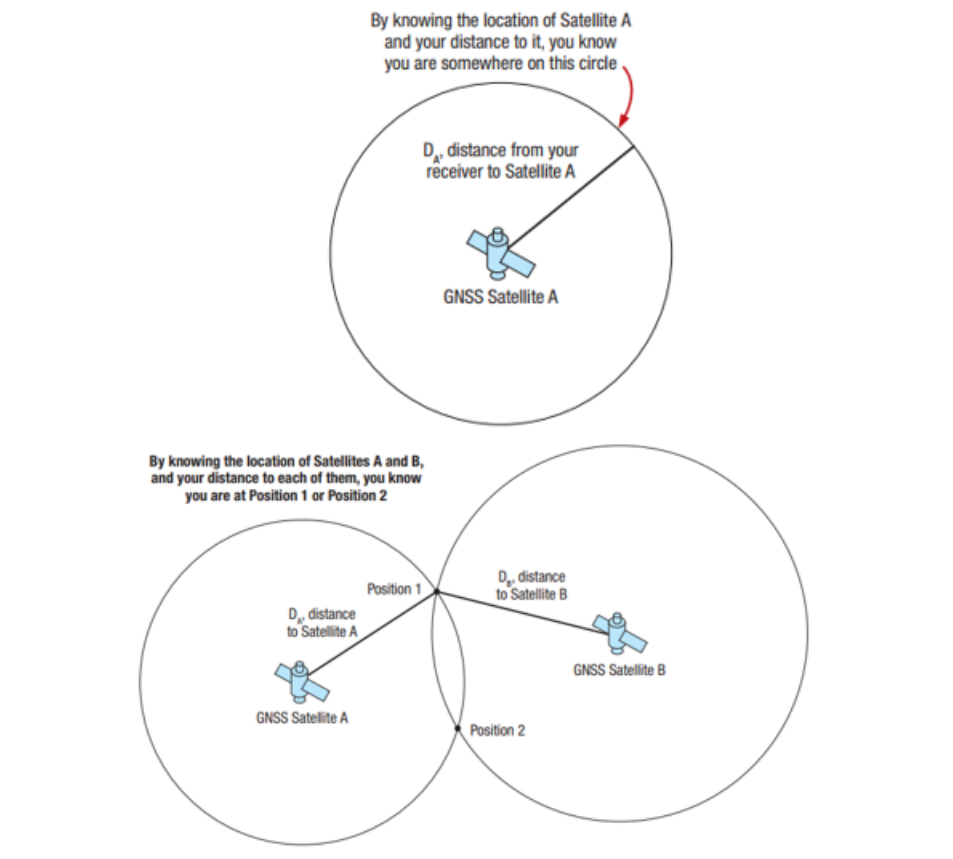


Figure 1.3.3.10: Geometric Principle of GNSS Positioning (Two-Dimensional Illustration) (Jeffrey, 2010).

Extending this reasoning to three dimensions, one might conclude that three ranges suffice. However, in practice, four pseudoranges are necessary due to inaccuracies in receiver clocks. Unlike the highly stable atomic clocks on board GNSS satellites, receiver clocks are usually quartz-based, with accuracies on the order of 5 parts per million. This results in range errors of up to ± 1500 m, which propagate directly into the position solution. When only three pseudoranges are used, the corresponding spheres do not intersect at a single point, due to clock bias (Fig. 1.3.3.11). GNSS receivers therefore treat the clock offset as an additional unknown and adjust their internal clock until all

pseudoranges converge at one solution. This technique effectively transfers the accuracy of satellite atomic clocks to the receiver, enabling it to compute both a precise position and a highly accurate time. Consequently, in three-dimensional positioning, four satellites are the minimum requirement: three to determine spatial coordinates and one to resolve the receiver clock bias.

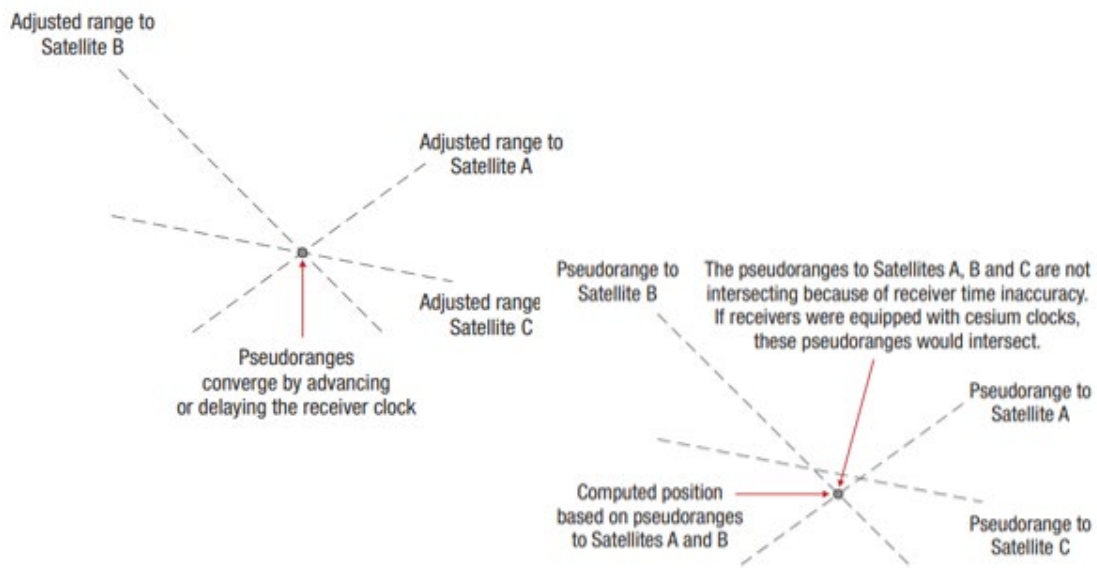


Figure 1.3.3.11: Solving for the Receiver Clock Error in GNSS Positioning (Jeffrey, 2010).

Computational Errors

Although GNSS receivers compute positions based on satellite data, several error sources degrade the solution if left uncorrected. These can be broadly divided into natural and artificial contributions:

- Atmospheric delays: refraction of signals in the ionosphere and troposphere alters propagation times, introducing systematic errors in pseudorange measurements.
- Multipath effects: reflected signals interfere with the direct signal, distorting the measured pseudoranges.
- Satellite-related errors: residual inaccuracies in the broadcast ephemerides or clock corrections.

- Receiver noise: limitations in hardware and signal processing introduce random errors.
- Artificial degradation: historically, intentional errors such as the U.S. Department of Defense's *Selective Availability (SA)* were introduced to limit civilian accuracy.

Mitigation strategies vary according to the error source. Dual-frequency measurements largely eliminate ionospheric delay; tropospheric delay can be modeled; multipath can be reduced through antenna design and advanced signal processing; satellite orbit/clock errors can be minimized by using precise corrections (e.g., from augmentation systems). Ultimately, the reliability of GNSS-derived positions depends not only on the measurement process but also on the effectiveness of error modeling and correction techniques.

Dilution of Precision (DOP)

The geometric distribution of satellites visible to a receiver significantly affects the accuracy of the computed position and time solution. This effect is quantified by the Dilution of Precision (DOP), a dimensionless factor that expresses how satellite geometry amplifies measurement errors.

When satellites are clustered in a small region of the sky, the intersection of pseudoranges becomes less distinct, and the resulting position estimate is spread over a larger area. Conversely, if satellites are widely separated, the geometry is stronger, leading to a more precise position determination (Fig. 1.3.3.12).

The general relationship is expressed as:

Inaccuracy of Position Measurement = DOP x Inaccuracy of Range Measurement

Thus, a small DOP value corresponds to favorable satellite geometry and higher positioning accuracy, while a large DOP indicates poor geometry and greater amplification of range errors.

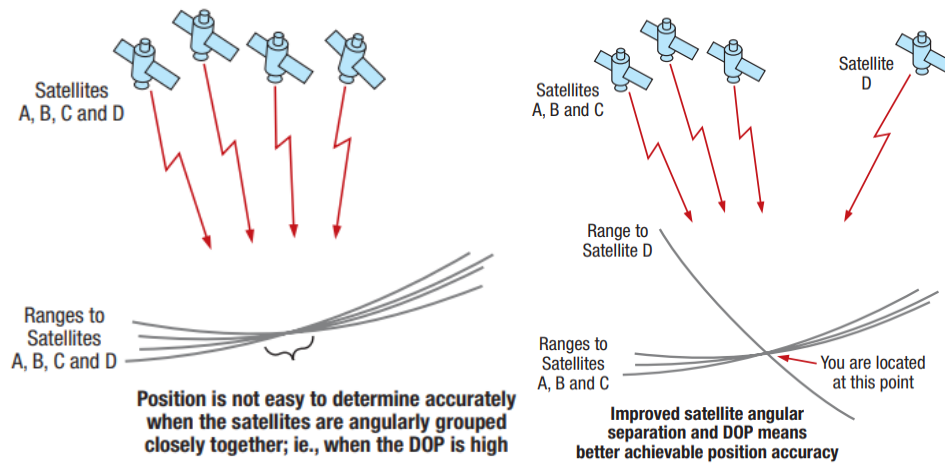


Figure 1.3.3.12: Influence of Satellite Geometry on Positioning Accuracy (Dilution of Precision)

Different components of DOP quantify accuracy in specific dimensions:

- **HDOP (Horizontal DOP):** relates to latitude and longitude accuracy.
- **VDOP (Vertical DOP):** relates to altitude accuracy.
- **PDOP (Position DOP):** relates to three-dimensional positioning accuracy.

These components are mathematically related and depend on the relative positions of the satellites. For instance, when satellites are low on the horizon, HDOP may be favorable but VDOP can be degraded, leading to poor altitude determination. Conversely, when satellites are clustered overhead, VDOP improves but HDOP worsens. At high latitudes (e.g., in Canada), GNSS satellites are observed at lower elevation angles, which can make achieving optimal VDOP challenging. Similarly, environments such as urban canyons or open-pit mines restrict satellite visibility and often produce unfavorable geometries, resulting in high DOP values. In operational contexts where satellite visibility is constrained, mission planning tools can be employed to identify time periods when DOP values are minimized, thereby improving positioning accuracy for critical applications.

Resolving Errors

The resolution of errors constitutes a fundamental aspect of GNSS receiver performance. The greater the receiver's ability to mitigate or eliminate errors, the higher the achievable accuracy and reliability of positioning. There is, however, no universally optimal method for error correction, as the choice of technique depends on the specific performance requirements of the application. Trade-offs typically involve accuracy, system complexity, solution availability, reliability, and cost. At the foundation of GNSS positioning lies the simple physical relationship:

$$\text{Velocity} = \text{Distance} \div \text{Time}$$

Accordingly, all factors influencing either the measured distance to the satellite or the signal travel time must be addressed. Several error mitigation strategies have been developed, which can be broadly categorized as follows:

- **Averaging:** repeated observations at the same location (least efficient method).
- **Modeling:** mathematical representation of the error-inducing phenomenon to predict and correct its effect.
- **Differential corrections (DGNSS):** comparison of signals received at two locations, one at a known reference station, to estimate and apply corrections.

The ability of modern receivers to exploit multiple constellations and multiple frequency bands significantly enhances error mitigation and overall positioning performance.

Multi-frequency receivers are highly effective in correcting for ionospheric delays, as the error varies with signal frequency. By comparing propagation delays of two signals (e.g., L1 and L2), the receiver can estimate and compensate for ionospheric effects. Furthermore, multi-frequency capability increases robustness against signal interference.

Receivers capable of accessing signals from multiple constellations (e.g., GPS, GLONASS, BeiDou, Galileo) benefit from a larger number of satellites in view, which improves spatial geometry and dilution of precision (DOP), reduces signal acquisition time, and mitigates challenges caused by obstructions such as buildings or vegetation. In GPS-only mode, at least four satellites are required to determine a position fix; in multi-constellation mode, at least five are needed, with one belonging to an additional constellation to resolve inter-system time offsets.

The traditional code-based positioning techniques rely on the pseudorandom noise (PRN) codes transmitted by satellites, achieving accuracies on the order of a few meters. For high-precision applications, such as geodesy and surveying, carrier-phase-based techniques, such as Real-Time Kinematic (RTK) and Precise Point Positioning (PPP), have been developed.

Carrier-phase measurements exploit the carrier wave of GNSS signals, which has a wavelength shorter than one meter (e.g., 19 cm for L1). This allows position measurements with millimetric precision. However, the inherent ambiguity in determining the exact number of carrier cycles between the satellite and the receiver must be resolved. Accurate positioning is achieved through:

- Pseudorange (code-based) position initialization.
- Mitigation of systematic errors using relative positioning or correction data.
- Exploitation of multiple simultaneous satellite observations to resolve carrier phase ambiguities.

Both RTK and PPP employ these principles, albeit through different computational strategies. Ultimately, the choice between code-based and carrier-phase techniques determines the level of positioning accuracy attainable, with carrier-phase methods providing performance superior by several orders of magnitude.

Differential GNSS - DGNSS

A widely employed technique for enhancing GNSS performance is Differential GNSS – DGNSS (Fig. 1.3.3.13). In this approach, the position of a fixed GNSS receiver, referred to as the *base station*, is determined with high accuracy using conventional surveying methods. The base station then computes the ranges to the GNSS satellites in view by means of code-based positioning techniques, combined with the satellites' positions derived from the broadcast orbital ephemerides and clock data.

The base station subsequently compares its precisely surveyed location with the position calculated from the satellite ranges. The discrepancies observed are attributable to satellite ephemeris and clock errors, but predominantly to atmospheric propagation delays. These corrections are transmitted from the base station to mobile receivers (*rovers*), which incorporate them into their own position calculations.

Differential positioning requires a data link between the base station and the rovers when corrections must be applied in real time, as well as the availability of at least four GNSS satellites in view from both the base station and the rovers. The absolute accuracy of the rover's computed position is directly dependent on the absolute accuracy of the surveyed position of the base station.

Because GNSS satellites orbit at high altitudes, the signal propagation paths from the satellites to the base station and to the rovers pass through nearly identical atmospheric conditions, provided that the base-to-rover separation is not excessive. In practice, differential GNSS performs effectively for separations of up to several tens of kilometres.

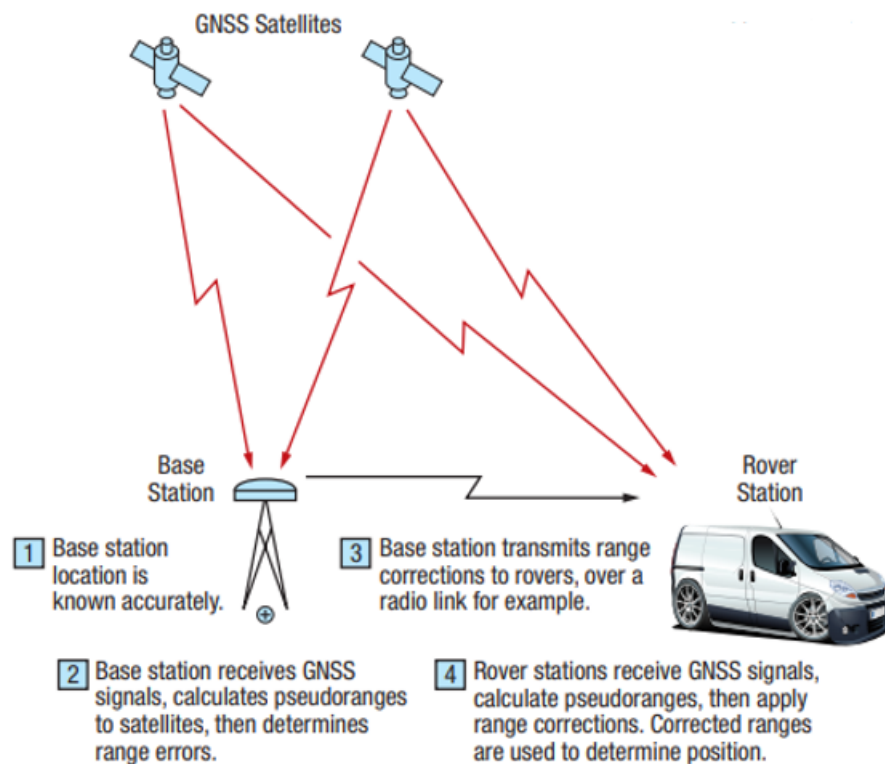


Figure 1.3.3.13: Operational Flow of Differential GNSS (DGNSS) Correction (Jeffrey, 2010).

Satellite-Based Augmentation Systems (SBAS)

For applications in which the cost of deploying a differential GNSS infrastructure is not justified, or when rover stations are dispersed over excessively large areas, a Satellite-Based Augmentation System (SBAS) offers a practical alternative for enhancing positioning performance. SBAS comprises geostationary satellite systems designed to improve the accuracy, integrity, and availability of core GNSS signals (Fig. 1.3.3.14).

An SBAS architecture typically includes a network of reference stations, master stations, uplink stations, and geostationary satellites (orbital period equal to the Earth's sidereal day). The reference stations, strategically distributed across the SBAS service area, continuously receive GNSS signals and transmit the data to the master station. Because the precise locations of the reference stations are known, the master station can compute wide-area correction parameters with high accuracy.

These corrections are subsequently transmitted to the SBAS satellites via uplink stations and then broadcast to user receivers within the coverage area. GNSS user equipment receives the correction messages and applies them to its range measurements, thereby significantly improving the reliability and accuracy of the computed position.

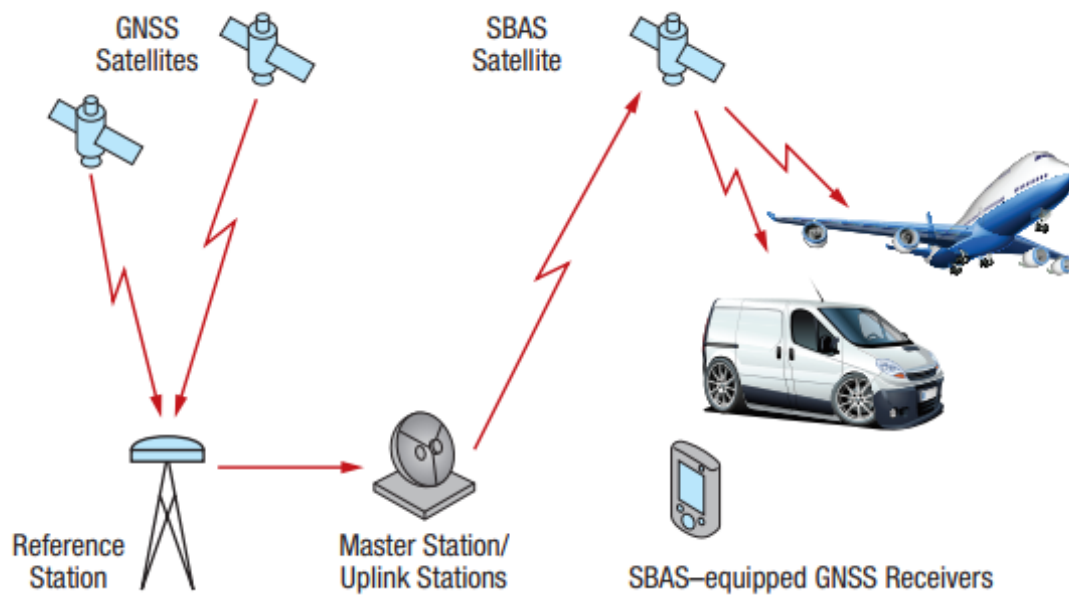


Figure 1.3.3.14: Architecture and Operational Flow of a Satellite-Based Augmentation System (SBAS) (Jeffrey, 2010).

Real-Time Kinematic (RTK)

In code-based positioning techniques, the receiver correlates and exploits the pseudorandom codes transmitted by at least four satellites to determine satellite ranges. By combining these ranges with the known satellite positions, the receiver can compute its location with an accuracy on the order of a few metres. For applications requiring higher precision, the RTK technique (Fig. 1.3.3.15) can be employed. RTK uses the carrier phase to provide ranges—and consequently positions—with accuracies several orders of magnitude higher than those achievable with code-based methods. Although RTK techniques are inherently complex, their underlying principle is the mitigation and removal of errors common to the base station–rover pair. Conceptually, the range is obtained by determining the number of carrier cycles between the satellite and

the rover and multiplying this value by the carrier wavelength. The resulting ranges inevitably include errors caused by satellite ephemeris and clock inaccuracies, as well as ionospheric and tropospheric delays. To eliminate these errors and fully exploit the precision of carrier-phase measurements, RTK requires the transmission of base station observations to the rover. A critical step in this process is ambiguity resolution, which consists of determining the integer number of carrier cycles. Rover receivers compute their position through algorithms that integrate ambiguity resolution with differential corrections. As with Differential GNSS (DGNSS), the achievable accuracy depends on the rover–base station separation (the *baseline*) and on the quality of the differential corrections. The latter, in turn, depend on the accuracy of the surveyed position of the base station and the quality of its satellite observations. Site selection, as well as the quality of base stations, rover receivers, and antennas, is essential to minimizing environmental effects such as interference and multipath.

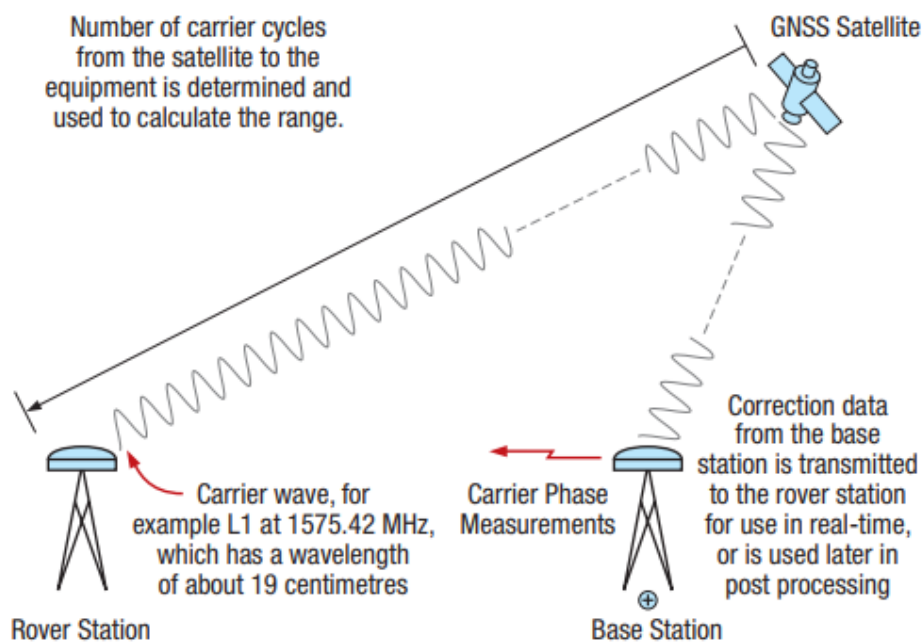


Figure 1.3.3.15: Principle of Real-Time Kinematic (RTK) Positioning (Jeffrey, 2010).

RTK networks rely on the deployment of multiple continuously operating reference stations (CORS) distributed over a wide area. The positioning data from these permanent stations are regularly transmitted to a central processing

facility. Upon request from RTK users, whose receivers provide an approximate position to the control centre, the latter computes and transmits either correction data or corrected positions back to the user's rover receiver. The main advantage of this network-based approach lies in the reduced number of RTK stations required, since the corrections can be distributed via radio or wireless communication links.

Precise Point Positioning (PPP)

Precise Point Positioning – PPP (Fig. 1.3.3.16) is a GNSS positioning technique that mitigates or models system-related errors to deliver high-accuracy positioning using a single receiver, without the need for a local base station. A PPP solution relies on precise satellite orbit and clock corrections, which are derived from a global network of continuously operating reference stations. Once computed, these corrections are disseminated to end users via geostationary satellites or internet-based services.

By applying these corrections, a receiver can achieve decimetre-level or better accuracy. However, PPP solutions typically require a convergence period before reaching such levels of precision. This convergence phase is necessary to resolve local biases introduced by atmospheric conditions, multipath effects, and satellite geometry. The final accuracy and the required convergence time are contingent upon the quality of the corrections and the algorithms implemented in the receiver. Under optimal conditions, PPP can achieve accuracies of up to 3 centimetres.

Structurally, PPP resembles Satellite-Based Augmentation Systems (SBAS), in that both provide correction messages to improve user positioning. However, PPP generally offers higher levels of accuracy, often on a subscription basis, and supports global coverage through a single correction stream, whereas SBAS systems are regionally constrained.

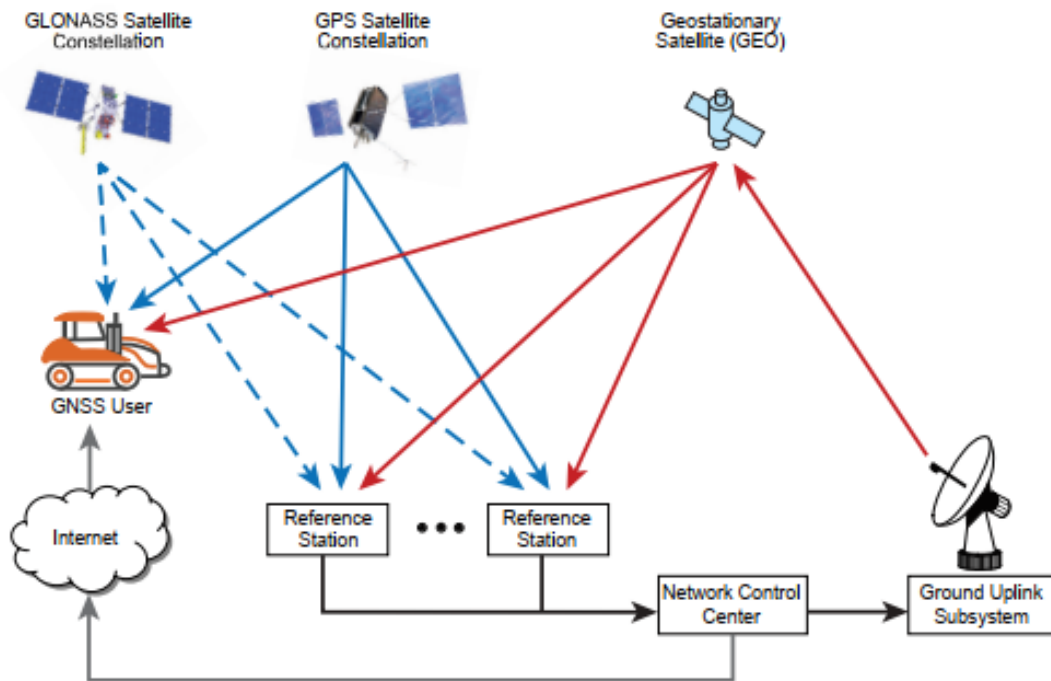


Figure 1.3.3.16: Precise Point Positioning (PPP) System Overview (Jeffrey, 2010).

Selecting the Most Suitable GNSS Correction Technique

As previously noted, there is no universally superior correction method; rather, the most appropriate approach depends on the intended application. The following provides a comparison of the main correction techniques.

DGNSS vs RTK: The configurations of DGNSS and RTK systems are similar, as both require a base station at a known location, a rover receiver that obtains corrections from the base station, and a communication link between the two. The primary difference lies in the measurement technique: RTK, which is based on carrier-phase observations, provides significantly higher accuracy than DGNSS, which relies on code measurements. The advantage of DGNSS is that it performs effectively over longer baselines and is generally less expensive than RTK.

SBAS vs PPP: SBAS and PPP systems are similar in that both receive corrections from satellites. However, PPP provides higher accuracy, since it employs carrier-phase-based corrections and typically operates as a private,

multi-frequency, multi-constellation service. The advantage of SBAS lies in its free availability: because it is code-based, it does not require ambiguity resolution, and its maximum accuracy is available almost instantaneously. By contrast, PPP requires an initial convergence period to resolve ambiguities before reaching full accuracy.

DGNSS vs SBAS: Although the accuracy of SBAS and DGNSS solutions is comparable, the infrastructure requirements differ. SBAS requires only an SBAS-compatible receiver and a GNSS antenna. DGNSS, by contrast, requires a base station with an antenna, a rover receiver with an antenna, a communication link between them, and the precise knowledge of the base station's position.

RTK vs PPP: RTK and PPP deliver comparable levels of accuracy but differ in configuration and operational requirements. RTK offers higher precision and faster initialization, but it is more expensive and complex, as it requires at least two capable receivers (a base station and one or more rovers), an antenna for each, and a communication link between them. Moreover, high accuracy depends on the base station being located at a precisely known position, and RTK performance degrades as the baseline length increases. In contrast, PPP requires only a single PPP-capable receiver, an antenna able to track GNSS and L-band signals, and a subscription to a correction service provider. However, it generally involves a longer convergence time and slightly lower accuracy than RTK. An additional advantage of PPP is its global applicability: since it does not rely on a base station, it provides consistent accuracy worldwide.

2. Data Processing Methodology

In this section, the methodology adopted for the analysis of GNSS and InSAR data used in the investigation of slope deformations at the two case studies—namely, the Cuenca landslide and the Fiastra Deep-Seated Gravitational Slope Deformation (DSGSD)—is presented.

2.1 GNSS Data Analysis

GNSS data were processed using RTKLib (Takasu et al., 2007; Takasu, 2009), an open-source software package designed for both standard and precise positioning with the Global Navigation Satellite System. RTKLib consists of a portable program library and a suite of application programs (APs) built upon it (Fig. 2.1.1). These can be operated either through a graphical user interface (GUI) or a command-line interface (CUI AP) and support a wide range of positioning algorithms for GPS, GLONASS, Galileo, QZSS, and BeiDou constellations, as well as SBAS. The software allows for several positioning modes, including both real-time and post-processing applications: Single, DGPS/DGNSS, Kinematic, Static, Moving-Baseline, Fixed, PPP-Kinematic, PPP-Static, and PPP-Fixed. In this study, millimetric accuracy was required; therefore, all analyses were performed in post-processing using the RTKPost module of RTKLib. This processing requires RINEX observation files from both the rover and the base station, along with correction files providing satellite ephemerides, clock data, and ionospheric and tropospheric models.

The Receiver Independent Exchange Format (RINEX) was first developed by the Astronomical Institute of the University of Bern to facilitate the exchange of GPS data collected during the large-scale European campaign EUREF 89. Today, RINEX represents the industry standard for GNSS data. Since many GNSS receivers record raw satellite observations in proprietary formats, which can only be processed by specific software, conversion to RINEX ensures interoperability.

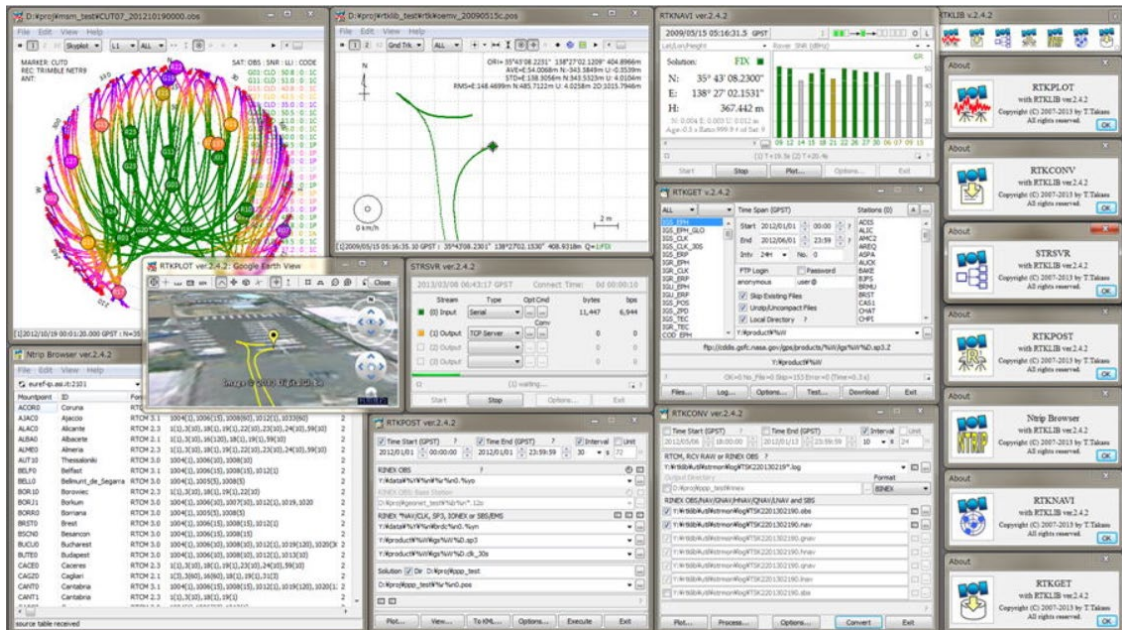


Figure 2.1.1: Graphical interface of the RTKLib software.

A RINEX file (Fig. 2.1.2) is an ASCII text file containing satellite observations, with a naming convention typically structured as:

4. NAME (e.g., STA1): receiver identifier
5. DOY: day of the year (Julian date)
6. S: session number (e.g., daily or hourly)
7. YY: two-digit year
8. Suffix: identifies the file type (e.g., “o” for observation)

Thus, a file named STA10030.16o would represent an observation file collected by receiver STA1 on day 30 of 2016. Each file consists of two parts: a header section, which contains metadata about the receiver setup and acquisition parameters (RINEX version, antenna characteristics, acquisition interval, time span, GNSS system, and visible satellite constellations), and a data section, which contains the actual satellite observations, typically organized in epochs defined by the logging rate of the receiver.

```

2.11          OBSERVATION DATA      M (MIXED)          RINEX VERSION / TYPE
CONVBIN 2.4.3          20200218 084449 UTC PGM / RUN BY / DATE
log: C:\data\Fiastra\output\2016\003\STA1.ubx          COMMENT
format: u-blox, option: -TADJ=1.0          COMMENT
Created by ubx2rnrx2          COMMENT
STA1          MARKER NAME
yetitmoves          yetitmoves          MARKER NUMBER
          0.0000          0.0000          0.0000          OBSERVER / AGENCY
          0.0000          0.0000          0.0000          REC # / TYPE / VERS
1          1          ANT # / TYPE
4          C1          L1          D1          S1          APPROX POSITION XYZ
30.000          ANTENNA: DELTA H/E/N
2016          1          3          0          0          0.0000000          GPS          WAVELENGTH FACT L1/2
2016          1          3          23          59          30.0000000          GPS          # / TYPES OF OBSERV
          INTERVAL
          TIME OF FIRST OBS
          TIME OF LAST OBS
          END OF HEADER

16 1 3 0 0 0.0000000 0 8G31G12G26G29G14G 2G25G21
21799940.680 114559467.002 1406.918 49.000
22831999.467 119982969.742 -2838.275 47.000
24910556.536 130905859.072 2868.198 42.000
20274376.509 106542625.437 292.587 51.000
24332699.416 127869181.284 -2996.438 41.000
23331599.899 122608400.836 -2327.087 46.000
20648113.442 108506602.040 -1034.930 50.000
24486546.224 128677657.267 3087.061 42.000
16 1 3 0 0 30.0000000 0 8G31G12G26G29G14G 2G25G21
21492162.010 112942075.586 1390.411 49.000
22548427.786 118492794.458 -2845.172 47.000
24594388.719 129244389.144 2867.709 42.000
19972953.626 104958637.582 277.931 51.000
24050027.172 126383734.151 -3002.333 41.000
23045128.968 121102982.896 -2340.287 46.000
20354261.987 106962404.175 -1047.053 50.000

```

Figure 2.1.2: Example of a RINEX file.

From RTKLaunch (Fig. 2.1.3a), the user can access RTKPlot (Fig. 2.1.3b) to visualize satellite data. In this module, all satellites observed by the station can be displayed, with red lines indicating signal loss. Each satellite is identified with an abbreviation, such as “G” for GPS satellites. Data can also be visualized through a skyplot (Fig. 2.1.3c), providing an overview of the satellite constellation geometry.

For accurate positioning, correction files are required, including satellite clocks, ephemerides, and ionospheric and tropospheric models. These were downloaded from the NASA CDDIS archive (<https://cddis.nasa.gov/archive/gnss/products/>).

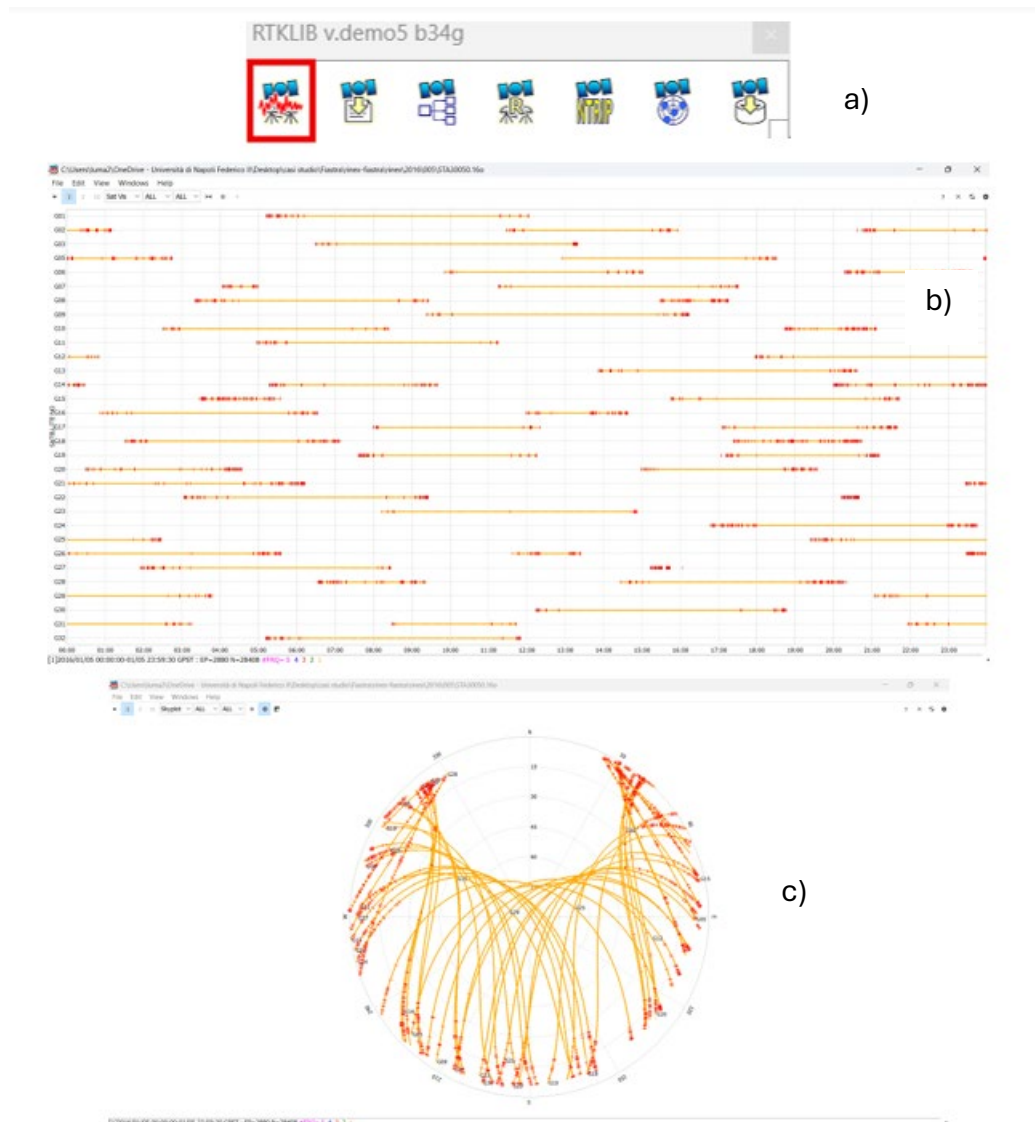


Figure 2.1.3: a) RTKLaunch interface; b) RTKPlot interface; c) Skyplot representation in RTKPlot.

Position corrections were performed using the RTKPost module (Fig. 2.1.4), which requires as input the rover RINEX files, the base station RINEX file, and the correction files. In addition, it is necessary to define several processing parameters in the options panel, including: positioning mode, signal frequencies, filter type, elevation mask, ionospheric and tropospheric correction models, satellite ephemerides and clock files, satellite constellations acquired by the receiver.

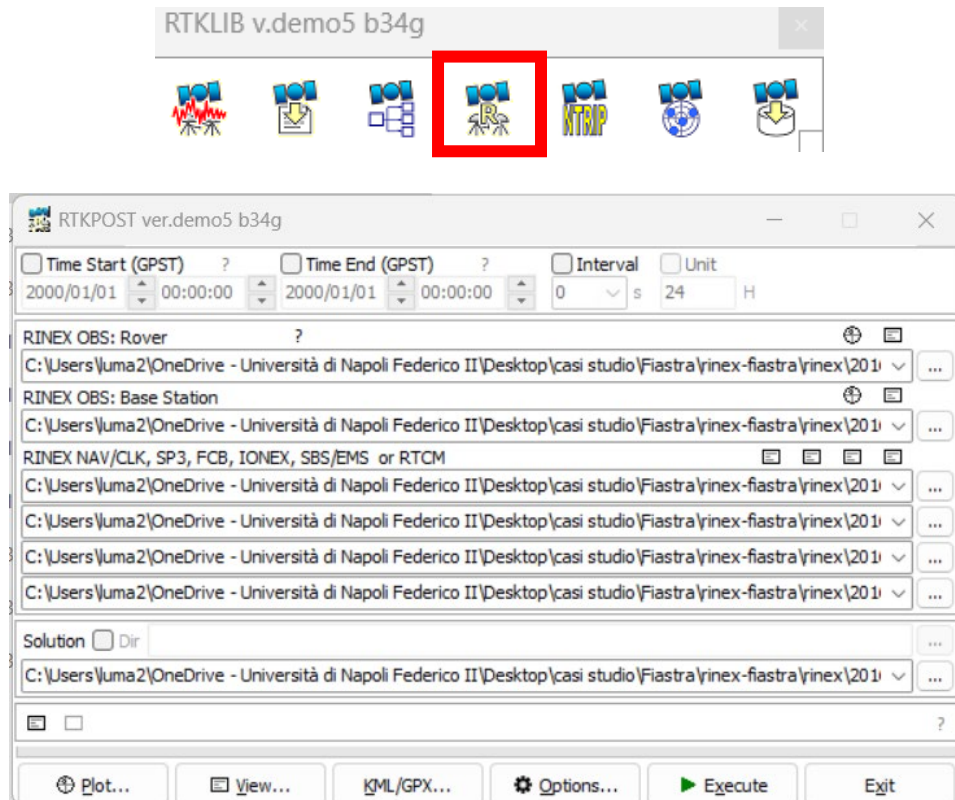


Figure 2.1.4: RTKPost module of RTKLib.

Given the large volume of data (daily acquisitions over multiple years), it was impractical to process files manually. Since RTKLib provides a command-line interface, the procedure was automated to ensure efficiency and reproducibility. To this end, a configuration file (Fig. 2.1.5) was created, containing all the RTKPost parameters defined in the *Options* section. Subsequently, Python scripts were developed to automate the workflow. The first script accessed the NASA archive to download the required correction data for each observation day. A second script (Fig. 2.1.6) invoked RTKPost to perform data processing and generate corrected rover positions relative to the base station, incorporating the downloaded correction files. This procedure yielded, for each day, the estimated position of each rover (Fig. 2.1.7) in the three coordinate components (East, North, Up), along with quality indicators and associated errors (standard deviation).

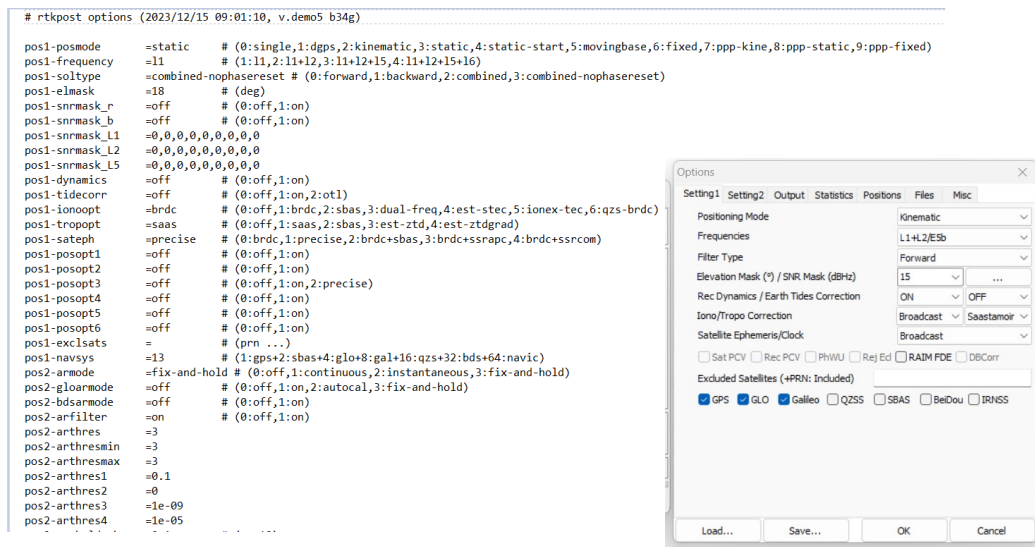


Figure 2.1.5: Configuration file example, displaying the processing parameters established in the RTKPost options section.

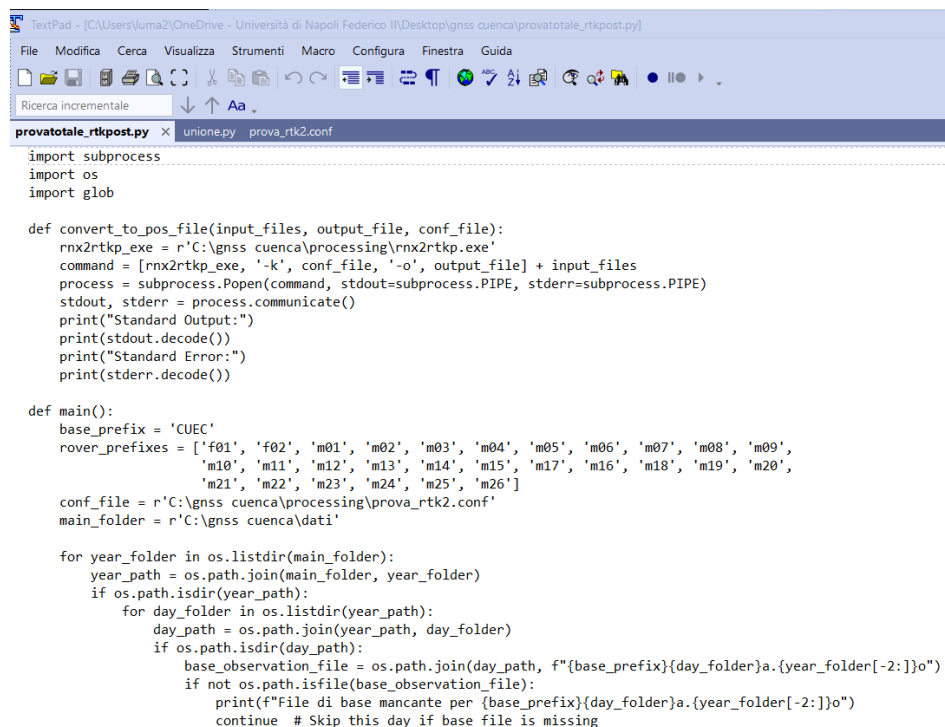


Figure 2.1.6: Python script designed for the automated processing of GNSS data using RTKPost.

```

% program : RTKLIB ver.demo5 b34g
% inp file : C:\gnss cuenca\dati\2021\194\m03.21o
% inp file : C:\gnss cuenca\dati\2021\194\CUEC194a.21o
% inp file : C:\gnss cuenca\dati\2021\194\m03.21n
% inp file : C:\gnss cuenca\dati\2021\194\COD0MGXFIN_20211940000_01D_05M_ORB.SP3
% inp file : C:\gnss cuenca\dati\2021\194\COD0MGXFIN_20211940000_01D_30S_CLK.CLK
% inp file : C:\gnss cuenca\dati\2021\194\c1pg1940.21i
% obs start : 2021/07/13 13:31:05.0 GPST (week2166 221465.0s)
% obs end : 2021/07/13 15:31:30.0 GPST (week2166 228690.0s)
% pos mode : Static
% freqs : L1+L2/E5b
% solution : Combined-No Phase Reset
% elev mask : 15.0 deg
% dynamics : on
% tidecorr : off
% ionos opt : Broadcast
% tropo opt : Saastamoinen
% ephemeris : Precise
% navi sys : GPS GLONASS Galileo BDS
% amb res : Fix and Hold
% amb glo : Fix and Hold
% val thres : 3.0
% antenna1 : ( 0.0000 0.0000 0.0000)
% antenna2 : ( 0.0000 0.0000 0.0000)
% ref pos : -2.883296737 -79.002484249 2634.1260
%
% (e/n/u-baseline=WGS84,Q=1:fix,2:float,3:sbas,4:dgps,5:single,6:ppp,ns=# of satellites)
% GPST e-baseline(m) n-baseline(m) u-baseline(m) Q ns sde(m) sdn(m) sdu(m) sden(m) sdnu(m) sdue(m) age(s) ratio
2021/07/13 13:31:05.000 203.3537 -3817.5465 -99.9792 1 8 0.0003 0.0002 0.0007 -0.0001 -0.0001 -0.0002 0.00 3.9

```

Figure 2.1.7: Example of daily rover position solutions.

For the complete analysis, daily solutions were merged to generate continuous time series. As shown, each rover position was available in terms of E, N, and Up components. Plotting these values against time enabled the reconstruction of displacement time series.

The workflow was designed to automatically scan the main data directory, identify subfolders corresponding to observation years and days, extract the rover and base RINEX files along with correction files, and process them according to the predefined configuration. The output consisted of daily average positions in three spatial components, quality metrics, and standard deviations—typically on the order of a few hundredths of a millimeter (Fig. 2.1.8). This level of precision confirms the robustness of the methodology and the reliability of the obtained results. Once the daily solutions were obtained for

each monitoring point, they were aggregated into long-term displacement time series covering the entire monitoring period.

% GPST	e-baseline(m)	n-baseline(m)	u-baseline(m)	Q	ns	sde(m)	sdn(m)	sdu(m)	sden(m)	sdnu(m)	sdu(m)	age(s)	ratio
2021/07/20 13:32:35.000	87.0645	-3694.3699	-99.4769	1	8	0.0002	0.0002	0.0005	-0.0000	0.0002	0.0000	0.00	62.4
2021/09/01 14:31:00.000	87.0631	-3694.3712	-99.4684	1	9	0.0002	0.0002	0.0008	0.0001	0.0002	0.0003	0.00	6.0
2021/09/17 14:29:50.000	87.0679	-3694.3753	-99.4851	1	9	0.0002	0.0002	0.0006	0.0000	0.0002	-0.0000	0.00	49.5
2021/10/21 14:38:25.000	87.0634	-3694.3608	-99.4718	1	7	0.0003	0.0002	0.0007	-0.0001	-0.0002	0.0002	0.00	32.9
2021/11/17 14:05:15.000	87.0590	-3694.3685	-99.4535	1	6	0.0003	0.0002	0.0008	-0.0000	-0.0003	-0.0002	0.00	58.0
2021/12/16 15:56:40.000	87.0639	-3694.3676	-99.4698	1	7	0.0003	0.0002	0.0007	-0.0000	0.0000	0.0002	0.00	35.0
2022/01/26 20:44:40.000	87.0574	-3694.3552	-99.4687	1	8	0.0003	0.0002	0.0007	-0.0001	0.0001	-0.0002	0.00	93.7
2022/02/23 19:44:25.000	87.0698	-3694.3401	-99.4715	1	9	0.0002	0.0002	0.0007	-0.0001	-0.0001	-0.0002	0.00	18.0
2022/03/17 16:45:50.000	87.0588	-3694.3596	-99.4816	1	8	0.0003	0.0002	0.0007	0.0001	0.0001	0.0001	0.00	11.0
2022/04/05 20:50:05.000	87.0874	-3694.3580	-99.5237	1	8	0.0003	0.0002	0.0007	-0.0001	0.0002	-0.0003	0.00	7.9
2022/05/16 13:50:40.000	87.0614	-3694.3669	-99.4731	1	9	0.0002	0.0002	0.0006	-0.0001	-0.0000	-0.0002	0.00	48.1
2022/06/21 15:39:35.000	87.0679	-3694.3677	-99.4920	1	8	0.0003	0.0002	0.0007	-0.0001	0.0003	-0.0002	0.00	40.5
2022/07/20 20:49:40.000	87.0581	-3694.3610	-99.4777	1	8	0.0003	0.0002	0.0005	0.0000	-0.0001	-0.0001	0.00	29.8
2022/08/31 14:35:25.000	87.0595	-3694.3643	-99.4701	1	10	0.0002	0.0002	0.0006	0.0001	0.0002	-0.0001	0.00	29.4
2022/09/29 14:02:00.000	87.0584	-3694.3682	-99.4725	1	9	0.0003	0.0002	0.0006	-0.0001	0.0001	-0.0001	0.00	44.4
2022/10/27 14:45:00.000	87.0489	-3694.3625	-99.4363	1	7	0.0003	0.0003	0.0007	0.0000	-0.0003	-0.0002	0.00	50.3
2022/11/28 13:48:35.000	87.0686	-3694.3651	-99.4553	1	10	0.0002	0.0002	0.0005	0.0001	0.0000	-0.0001	0.00	20.9
2023/01/27 13:27:40.000	87.0577	-3694.3734	-99.4825	1	8	0.0003	0.0002	0.0007	-0.0001	0.0002	-0.0002	0.00	62.6
2023/01/23 14:29:10.000	87.0652	-3694.3481	-99.4809	1	7	0.0004	0.0002	0.0007	-0.0002	0.0001	0.0004	0.00	19.2
2023/02/27 13:44:40.000	87.0618	-3694.3681	-99.4796	1	7	0.0002	0.0001	0.0004	0.0001	-0.0000	-0.0001	0.00	67.4
2023/03/23 14:12:41.000	87.0582	-3694.3575	-99.4745	1	7	0.0002	0.0001	0.0004	0.0000	-0.0001	0.0001	0.00	33.8
2023/04/25 13:56:38.000	87.0562	-3694.3652	-99.4814	1	9	0.0001	0.0001	0.0004	-0.0000	-0.0001	-0.0001	0.00	59.9
2023/05/24 15:32:13.000	87.0582	-3694.3569	-99.4922	1	9	0.0002	0.0001	0.0003	-0.0000	-0.0000	0.0001	0.00	24.4
2023/06/26 13:40:56.000	87.0537	-3694.3678	-99.4711	1	7	0.0002	0.0001	0.0004	-0.0000	0.0001	-0.0000	0.00	58.3
2023/07/17 13:38:40.000	87.0481	-3694.3616	-99.4719	1	9	0.0001	0.0001	0.0003	-0.0000	-0.0000	0.0001	0.00	19.7
2023/08/28 16:22:21.000	87.0499	-3694.3383	-99.4641	1	7	0.0002	0.0001	0.0003	0.0000	-0.0001	0.0001	0.00	15.3
2023/09/27 20:24:53.000	87.0598	-3694.3564	-99.4849	1	9	0.0002	0.0001	0.0003	0.0000	0.0001	0.0000	0.00	8.8
2023/10/23 15:06:03.000	87.0493	-3694.3442	-99.4512	1	9	0.0001	0.0001	0.0003	0.0000	0.0000	0.0001	0.00	6.3
2023/11/16 14:21:09.000	87.0567	-3694.3533	-99.4508	1	8	0.0001	0.0002	0.0005	-0.0001	0.0002	-0.0001	0.00	31.4
2023/12/19 14:03:21.000	87.0546	-3694.3470	-99.4479	1	7	0.0002	0.0001	0.0003	0.0000	0.0001	-0.0001	0.00	16.6
2024/01/26 14:00:04.000	87.0590	-3694.3572	-99.4716	1	7	0.0002	0.0001	0.0004	0.0000	-0.0001	-0.0001	0.00	19.5
2024/03/25 16:41:18.000	87.0548	-3694.3443	-99.4787	1	8	0.0001	0.0001	0.0003	0.0000	0.0001	0.0001	0.00	18.0
2024/04/24 14:10:47.000	87.0567	-3694.3591	-99.4736	1	9	0.0001	0.0001	0.0003	-0.0000	0.0000	0.0000	0.00	23.6
2024/05/29 14:25:41.000	87.0599	-3694.3742	-99.4703	1	9	0.0002	0.0001	0.0004	-0.0001	-0.0001	-0.0001	0.00	4.9

Figure 2.1.8: Example of a complete position solution for a rover over the monitoring period.

2.2 SAR Data Analysis

In addition to GNSS data analysis, interferometric SAR (InSAR) data were also exploited to obtain both a wide-area view of ongoing deformations and an independent validation of the GPS-based results. The approach, however, differed between the two case studies.

For the Fiastra DSGSD, the analysis relied on interferometric products already processed and made available by the European Ground Motion Service - EGMS (<https://egms.land.copernicus.eu/>) (Fig. 2.2.1). The EGMS provides InSAR displacement measurements in the satellite Line-of-Sight (LOS), consisting of geo-referenced points with annotated quality indicators and associated displacement time series. These products are derived from the interferometric processing of full-resolution Sentinel-1 radar images (20×5 m). The dataset includes measurement points from both ascending and descending orbits, color-coded according to their average velocity, and complemented by displacement histories. Such information offers valuable insights into the deformation patterns of the investigated slope and was used here to validate the GNSS-based results.

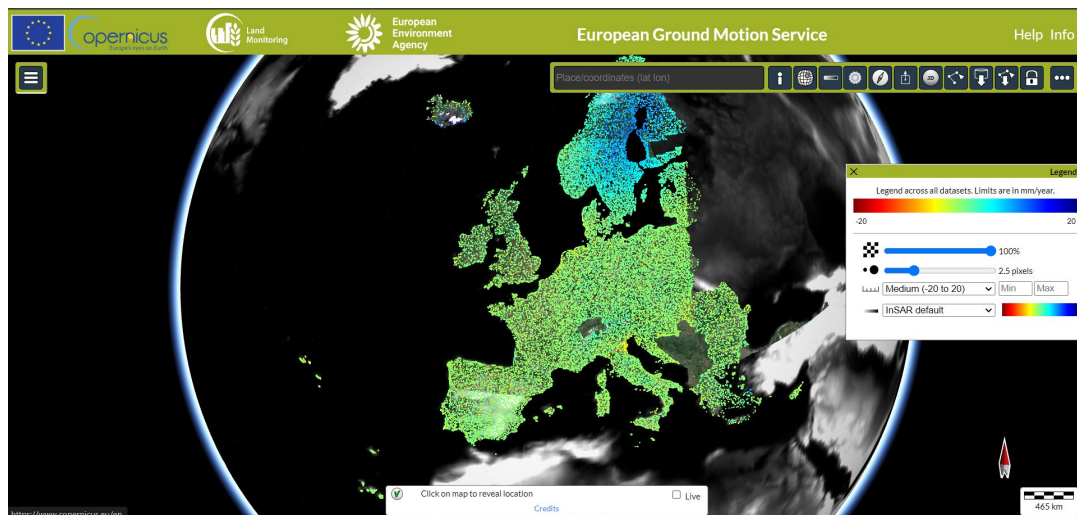


Figure 2.2.1: European Ground Motion Service - EGMS site.

For the Cuenca landslide (Ecuador), instead, the interferometric analysis was performed directly using the Multi-Temporal InSAR (MT-InSAR) approach, which processes time series of SAR acquisitions collected at multiple epochs

(Franceschetti & Lanari, 2018). Among the various MT-InSAR techniques, the Small BAseline Subset (SBAS) method (Berardino et al., 2002; Lanari et al., 2004) was adopted, as it constructs a network of interferograms with small spatial and temporal baselines, thereby improving phase coherence and enabling accurate displacement estimation. This technique is particularly suitable for analyzing Distributed Scatterers (DS)—radar targets characterized by gradual and continuous phase variations—which can also be identified in vegetated or non-urbanized areas (Berardino et al., 2002). In this context, C-band Sentinel-1 Single Look Complex (SLC) images were employed, as their lower frequency provides greater penetration through vegetation compared to X-band SAR, thereby enhancing the detection of ground deformations in forested environments (Li et al., 2023).

The analysis was carried out using the SUBSIDENCE software, based on the Coherent Pixel Technique (CPT) (Mora et al., 2003), developed at the Universitat Politècnica de Catalunya (UPC). Detailed descriptions of the algorithm are available in Blanco-Sanchez et al., (2008) and Iglesias et al., (2015). The dataset consisted of Sentinel-1A acquisitions (ascending and descending orbits) spanning the period from July 2021 to June 2024, with a 12-day revisit time.

When interpreting interferometric results, it is important to recall that SAR satellites operate in semi-polar (North–South) orbits and are therefore sensitive only to deformation components projected onto the West–East Line-of-Sight (Colesanti & Wasowski, 2006). More specifically:

- In ascending acquisitions, positive values indicate motion toward the satellite in the East–West direction, while negative values indicate displacement away from the satellite (West–East).
- In descending acquisitions, positive values indicate motion toward the satellite in the West–East direction, while negative values correspond to displacement in the opposite direction (East–West).

Finally, to better constrain the kinematics of the Cuenca landslide, the methodology proposed by M. Khalili et al., (2023) was applied. This approach incorporates the directional cosines of the satellite acquisition geometry to decompose LoS displacements into vertical and West–East components. Due to the orbital configuration, this decomposition is limited to these two directions, as displacements parallel to the satellite’s motion (North–South) cannot be detected. Consequently, landslides oriented predominantly along the North–South axis remain more difficult to capture compared to those with a significant West–East component.

3. Case Studies

This section of the thesis presents the application of monitoring techniques to two case studies: the DSGSD of Fiastra and the landslide affecting the University of Azuay in Cuenca (Ecuador). In both cases, previously conducted investigations documented in the scientific literature were considered, followed by the implementation of interferometric and geodetic monitoring techniques using GNSS.

3.1 Fiastra DSGSD

Deep-Seated Gravitational Slope Deformations (DSGSDs) are large-scale rock-mass movements that affect entire slopes or valleys (Agliardi et al., 2001; Dramis, 1984). They exhibit characteristic morphological and structural features (e.g. double crest lines, downhill-facing and counterslope scarps) and are typically associated with low displacement rates (from a few millimetres up to 1–2 cm yr⁻¹). Their activity can be modulated or triggered by several external factors, including precipitation, erosion, and seismic loading.

The Fiastra DSGSD is located in the Marche region (Italy) on the eastern flank of the central Apennines. It covers ≈ 5 km² and extends northward from the summit of Monte Frascare (≈ 1300 m a.s.l.) down to the Fiastrone valley floor (≈ 600 m a.s.l.), where the Fiastra reservoir and dam are situated.

From a stratigraphic and lithological perspective (Fig. 3.1.1), the area is part of the Umbro–Marchigiana succession (Lower Lias to Upper Eocene). The main lithostratigraphic units exposed in the study area are (Deiana et al., 2009):

- **Maiolica Formation** (Upper Tithonian – Lower Aptian). The Maiolica reaches several hundred metres in thickness and is mainly composed of whitish, dense limestones with conchoidal fracturing and interbedded grey to black cherts.
- **Marne a Fucoidi Formation** (Lower Aptian – Upper Albian). This unit comprises reddish, greenish and yellowish marls and clayey marls overlain by whitish marly limestones; it attains an average thickness of

≈60 m and represents the mechanically weakest lithology within the study area.

- **Scaglia Bianca Formation** (Upper Albian – Lower Turonian). Characterized by whitish limestones and marly limestones interbedded with black to reddish cherts, its thickness ranges between ≈60 and 70 m.
- **Scaglia Rossa Formation** (Lower Turonian – Lutetian). Constituted of reddish limestones and marly limestones with red cherts, this formation reaches several tens of metres in thickness.

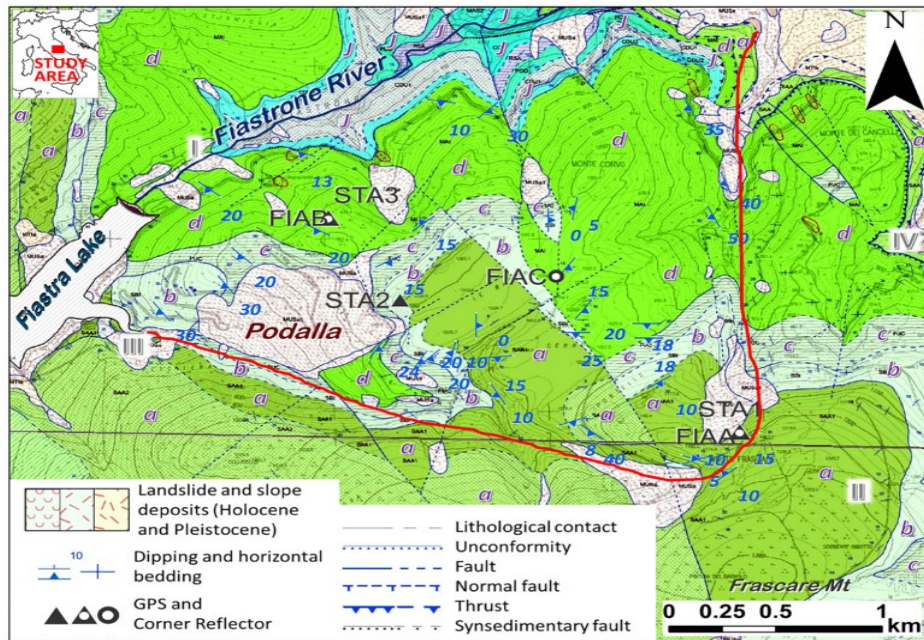


Figure 3.1.1: Geological map of the study area (modified after Carta Geologica Regionale 1:10000 – Regione Marche, 2014): a) Scaglia Rossa Fm – several members; b) Scaglia Bianca Fm; c) Marne a Fucoidi Fm; d) Maiolica Fm; J) Jurassic formations. I-II and III-IV represent the traces of the geological sections. Red line indicates the area involved in the slope deformation (Amato et al., 2018).

These sedimentary successions underwent compressional deformation during the Tortonian–Messinian, contributing to the building of the Apennine chain (Calamita et al., 1994). From the Late Pliocene–Early Pleistocene onwards, the area experienced extensional tectonics, leading to the opening of intermontane basins (Cavinato et al., 1994; Centamore et al., 2003). Consequently, faults of the Apenninic trend (N150°–170°), the anti-Apenninic trend (N30°–50°), and N–S striking structures have been mapped within the study area (Aringoli et al.,

2010; Tolomei et al., 2013). The Fiastrone River follows a major N30°–50° fault and has carved a deep gorge at the toe of the investigated slope. Remnants of the Pleistocene planation surface persist locally but are offset by steps, counterslopes and metre-scale scarps related to DSGSD activity (Fig. 3.1.2).

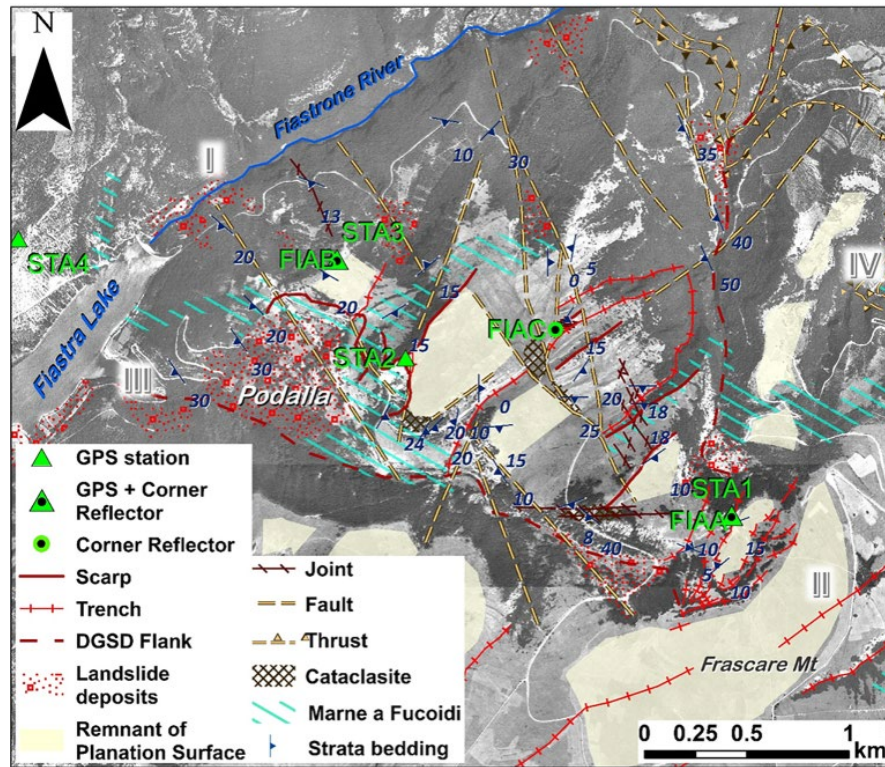


Figure 3.1.2: Geomorphological map of the study area (after Tolomei et al., 2013).

Tolomei et al. (2013) classified the Fiastra deformation as a *sackung*, slowly migrating NNW along a gently dipping sliding plane and bounded upslope by arcuate trenches. This is a seismically active area that was affected by the 2016–2017 Central Italy earthquake sequence:

- August 24, 2016, Amatrice earthquake (Mw 6.0);
- October 26, 2016, two earthquakes (Mw 5.9 and Mw 5.4);
- October 30, 2016, the strongest event of the sequence (Mw 6.5), 6 km north of Norcia;
- January 18, 2017, four earthquakes (Mw 5.0–5.4), 20 km south of Accumoli.

Since seismic activity can induce acceleration phases and/or partial collapses of DSGSDs, increasing the risk to people and infrastructure, several authors have investigated the correlation between seismicity and DSGSD movement. Particular attention has been given to monitoring techniques, aimed both at characterizing short- and long-term evolution and at defining deformation susceptibility. Specifically:

1. Albano et al. (2015) proposed the installation of GPS stations and corner reflectors to improve the poor radar coherence of the study area;
2. Polcari et al. (2017) used multiband differential SAR interferometry (DInSAR) to analyze displacements induced by the earthquake sequence in central Italy;
3. Amato et al. (2018) explored the integration of DInSAR and GPS data as a monitoring system for earthquake-triggered, slow-moving landslides.

The monitoring network consists of four single-frequency (L1) GPS stations (three rovers and one base station) equipped with professional receivers and antennas, powered by photovoltaic panels, and transmitting data in real time to the analysis centre of the National Institute of Geophysics and Volcanology (INGV) in Rome. The rovers (STA1, STA2, STA3) are distributed along the slope near the main geomorphological features of the DSGSD, while the base station (STA4) is located on the opposite side of the valley and serves as the reference point for all measurements (Figs. 3.1.3-3.1.4). Moreover, given the dense vegetation cover and the scarce, if not negligible, presence of natural InSAR reflectors, artificial corner reflectors were installed near STA1 and STA3 to improve radar coherence.

GPS stations, operating from October 2015 to January 2019, acquired measurements every 30 seconds. These receivers were capable of recording only GPS constellation signals at the L1 frequency. The resulting data enabled the reconstruction of displacement time series over the entire monitoring period.

To obtain a broader-scale perspective of slope stability, InSAR data were also downloaded from the EGMS platform. These products are derived from Sentinel-1 acquisitions in both ascending and descending geometries. The temporal coverage of the dataset spans from October 2015 to January 2019, with a revisit interval of 12 days. To enable direct comparison with the GPS data, the Line-of-Sight (LoS) displacements were decomposed into their East–West and Up–Down components. This approach allowed for a consistent comparison between GPS and InSAR time series and facilitated the identification of deformation patterns affecting the slope.

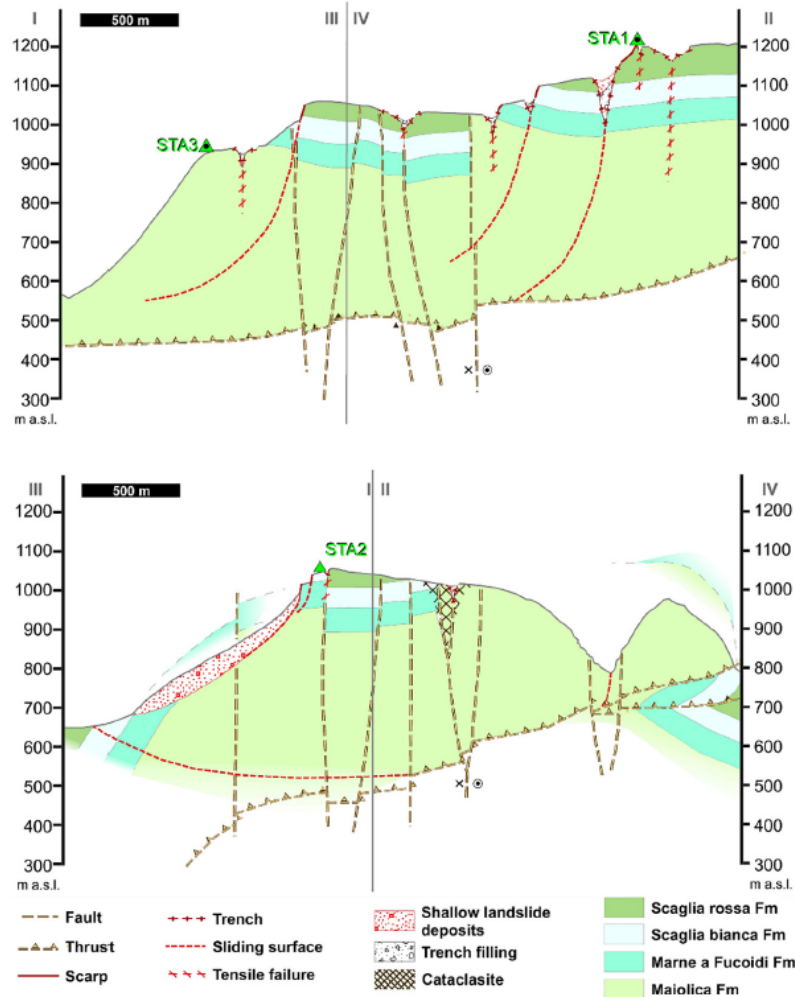


Figure 3.1.3: Geological sections with vertical exaggeration - 2:1 (after Amato et al., 2018).



Figure 3.1.4: Map showing the location of the GPS stations. The rovers are depicted in blue, while the base station is shown in magenta.

3.2 Cuenca landslide

Cuenca, like much of Ecuador, is highly susceptible to gravitational processes due to steep topography, active tectonics, and intense seasonal rainfall (Sellers et al., 2020; M. A. Khalili et al., 2024). This susceptibility is further exacerbated by rapid urban expansion into high-slope areas. A landmark event illustrating such vulnerability is the 1993 La Josefina landslide, which mobilized over 20 million cubic meters of material and temporarily dammed the Paute River, threatening Ecuador's main hydroelectric infrastructure.

The University of Azuay, which constitutes our case study, is located in the central-eastern sector of the Cuenca Basin, an intermontane depression in southern Ecuador (Azuay Province), situated between the Western and Eastern Cordilleras of the Andes. The area displays an altitudinal gradient ranging from ~2500 m to 4500 m a.s.l., shaped by long-term compressional tectonics and uplift associated with Andean orogeny. The Cuenca Basin rests upon a Paleozoic metamorphic basement and is filled with a complex sequence of Mesozoic to Quaternary marine, fluvial, and volcanic deposits. Pioneering geological studies on Ecuador and the Cordillera Real were conducted by Wolf (1892), Sauer (1958), Sauer et al. (1965), and Tschopp (1953). Later reconnaissance mapping and stratigraphic syntheses were carried out between the 1970s and 1980s by Kennerley et al. (1971), Kennerley (1973), C. R. Bristow (1973), all summarized by Baldock (1982). These works established the foundations for understanding the structural and stratigraphic evolution of the Cuenca region.

The basin is tectonically constrained by NE-SW trending faults (Bristow & Guevara, 1980; Hungerbühler et al., 2002), which have controlled both its formation and sedimentation styles. Two main depositional phases are recognized:

- First phase: continuous sedimentation in deltaic to marginal marine environments, mainly sourced from the Eastern Cordillera, characterized by metamorphic clasts, facies associations, and paleocurrent indicators.
- Second phase: a transition to coarse-grained fluvial and alluvial systems derived from the Western Cordillera, unconformably overlying deformed older units.

In the University of Azuay area and its surroundings, several stratigraphic units are present:

- **Yunguilla Formation (Maastrichtian–Paleocene):** defined by cherts, silicified greywackes, and shales with limestone lenses. Fossil assemblages include *Inoceramus. sp.*, *Hoploscaphites sp.*, and *Baculites sp.* (Bristow & Hoffstetter, 1977; Pratt et al., 2005; Khalili et al., 2023).
- **Turi Formation (Late Eocene–Oligocene):** alternating conglomerates (0.9–2.5 m thick), sandstones, and limonitic layers, indicative of high-energy environments.
- **Biblián Formation (Early Miocene):** up to 1200 m thick; composed of continental fluvial detrital deposits, micaceous and volcanic-rich sands, shales, and common gypsum nodules (Ministerio de Energía y Minas, 2000).
- **Loyola Formation (Middle Miocene):** grey shales and cream-colored claystones with quartz lenses and soft sandstones rich in iron oxides.
- **Azogues Formation (Late Miocene):** thick-bedded brown sandstones, shales, and conglomerates in fluvio-lacustrine environments. Spheroidal weathering is widespread, particularly in southern sectors.
- **Mangán Formation (Middle Miocene):** brown sandstones, green and red laminated shales, often associated with coal seams.

Each of these formations contributes to the structural and geotechnical complexity of the study area. For instance, the combination of weak lithologies

(Loyola and Mangán formations), high precipitation, and seismicity predisposes the area to shallow slope failures. This lithostratigraphic framework underpins both surface morphology and subsurface behavior across the University of Azuay and adjacent sectors (Fig. 3.2.1).

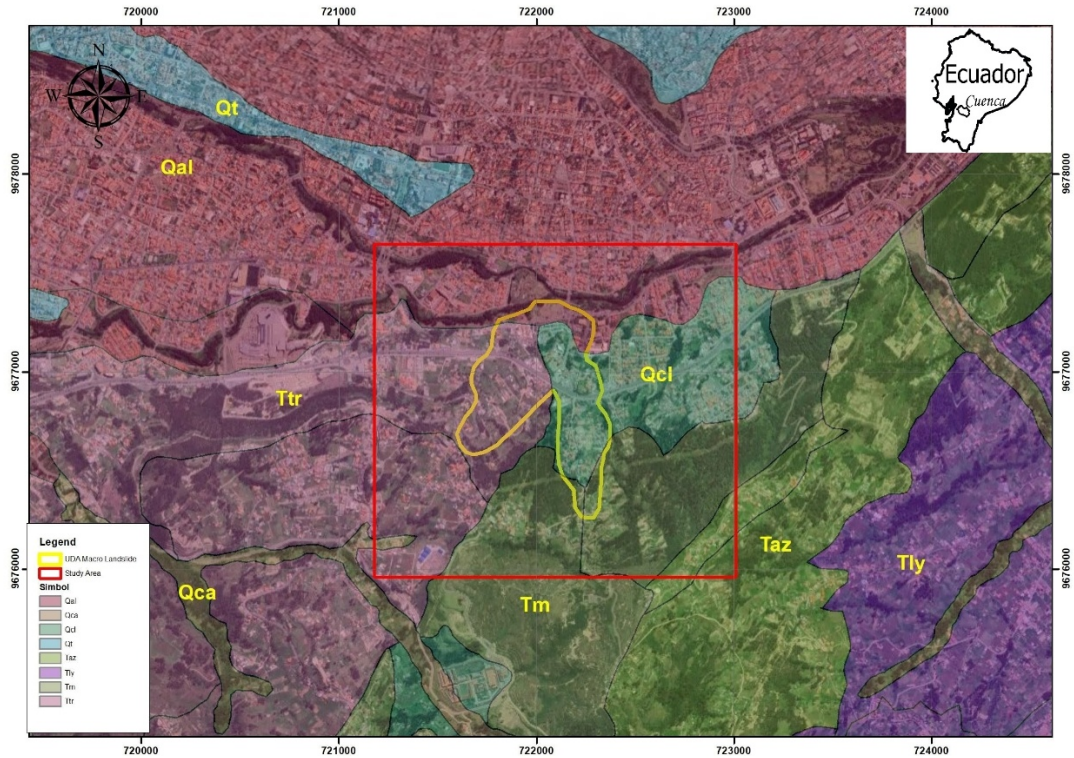


Figure 3.2.1: Geological sketch map of the area surrounding the UDA landslide (Cuenca, Ecuador). Loyola Formation (Tly), Biblián Formation (Tbi), Azogues Formation (Taz), Mangán Formation (Tm), and Turi Formation (Ttr), along with the Alluvial Terrace Deposits (Qt), Colluvio–Alluvial Deposits (Qca), Colluvial Slope Deposits (Qcl), and Alluvial Deposits (Qal). The yellow line delineates the UDA landslide, while the red box indicates the study area.

To complement the geological interpretation of the University of Azuay sector, a geophysical study was conducted using electrical resistivity tomography (ERT) and seismic refraction and reflection. These techniques provide high-resolution subsurface information relevant to stratigraphic interpretation, geotechnical characterization, and landslide risk modeling. The methodology follows protocols successfully applied in comparable Andean contexts, such as

those reported by Sellers et al. (2021), who investigated a strategic building within the campus affected by a slow-moving landslide.

Electrical resistivity tomography has proven effective in determining the geometry, depth, and resistivity of subsurface layers. This method is based on the variation of electrical resistivity of soils and rocks, which depends on mineralogy, water content, and porosity (García-Cortés et al., 2008). Conversely, seismic refraction techniques provide estimates of the elastic properties of materials, using the travel times of compressional (V_p) and shear (V_s) waves to delineate mechanical contrasts in the subsurface (Fernández Viejo, 1997). These methods are particularly suitable for detecting lithological changes, variations in moisture content, and groundwater presence.

A 155-m-long ERT survey line was conducted within the University of Azuay campus, employing a Wenner-Schlumberger array with 32 electrodes. The results revealed resistivity values ranging from 3 to >80 ohm. At depths of approximately 17 m, a low-resistivity zone was identified, interpreted as a saturated fine-grained layer or clay-rich horizon. Discrete high-resistivity blocks, possibly associated with volcanic lithologies or compacted sands, were also detected, suggesting post-depositional displacement or buried structural features.

The tomographic results were consistent with previous interpretations by Sellers et al. (2021), who identified similar resistivity anomalies linked to increased pore pressure and hydroplastic deformation. These findings support the hypothesis of a layered subsurface system with intercalated volcanic and sedimentary materials, prone to water retention and delayed drainage.

Seismic refraction surveys were carried out using two profiles: a 23 m line within the campus and a 36 m line outside the campus. Both configurations employed 24 geophones and an impulsive source, with inter-geophone spacing adapted to the terrain. In addition to standard refraction analysis, ReMi (Refraction Microtremor), MASW (Multichannel Analysis of Surface Waves),

and ESAC (Extended Spatial AutoCorrelation) tests were conducted to increase reliability. Results indicate a three-layer stratification:

- A shallow, low-velocity layer ($V_s < 200$ m/s), interpreted as loosely consolidated fill.
- An intermediate layer with moderate velocities (V_s 200–400 m/s), suggesting sandy silts with moisture.
- A deeper, compacted stratum ($V_s > 500$ m/s), consistent with lithified volcanic or sedimentary units.

The profiles confirmed water table depths at approximately 5 m, corroborating the resistivity model and DGPS-derived displacement vectors. As emphasized by Sellers et al. (2020), the integration of geophysical and geodetic data enables the early identification of sliding surfaces and the assessment of structural vulnerability. These geophysical insights have been critical for risk mitigation strategies around campus infrastructure. The combined use of ERT and seismic surveys aligns with international best practices for landslide-prone terrains in highland tropical environments.

The University of Azuay is located on a geomorphologically unstable slope in the southeastern part of Cuenca. The terrain is composed of interbedded sedimentary units of the Mangán, Turi, and Loyola formations, overlying older alluvial terraces and dissected by artificial cuts associated with infrastructure such as the Cuenca–Azogues highway. The slope morphology and subsurface stratigraphy favor the occurrence of slow-moving, shallow translational landslides.

GNSS data and Sentinel-1A radar images were analyzed and compared to investigate the stability of the landslide affecting the University of Azuay, located in the southeastern sector of Cuenca (Ecuador). To achieve high-precision monitoring of ground deformation, a geodetic network of 28 permanent fourth-order DGPS markers was established across the University of

Azuay campus and adjacent areas, including Av. 24 de Mayo and Calle Jacinto Flores (Fig. 3.2.2).

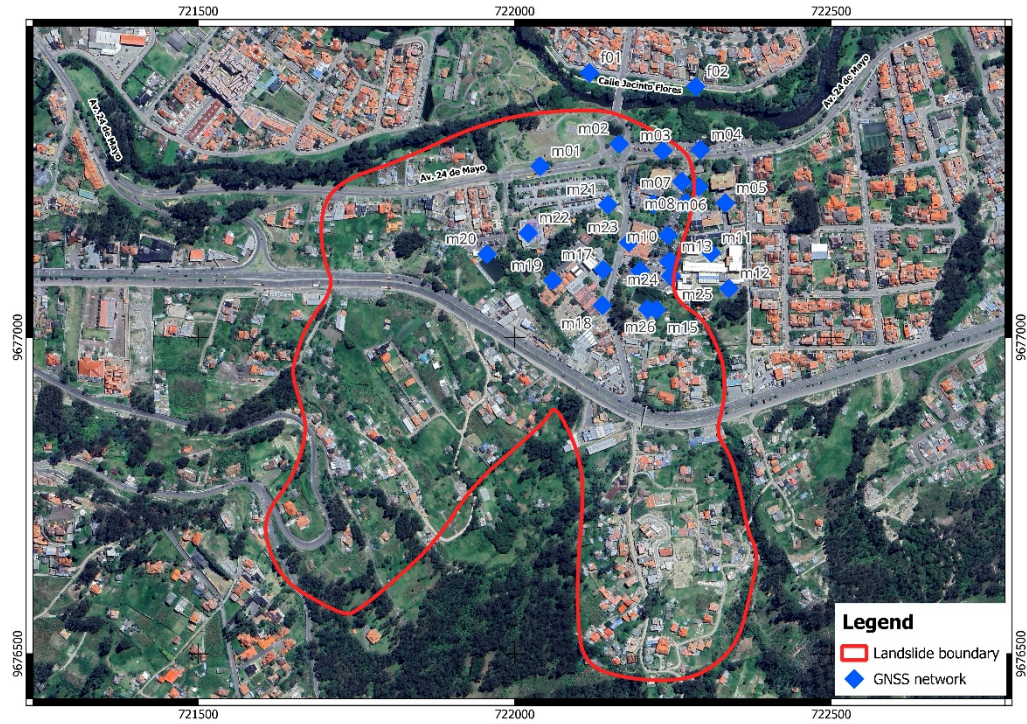


Figure 3.2.2: Georeferenced positions of GNSS monitoring stations in relation to the delineated landslide perimeter.

Each marker was built according to forced-centering specifications, consisting of buried concrete foundations (0.6–1.0 m depth) and steel plates (0.5×0.5 m) reinforced with iron cores, ensuring structural integrity with the moving soil mass. This design minimizes errors caused by marker instability or surface disturbance, thus guaranteeing that the recorded deformation reflects true ground motion.

GNSS data analysis was based on discrete measurements acquired during monthly survey campaigns conducted between July 2021 and June 2024 on the 28 DGPS markers of the geodetic network. Data were collected using a Trimble R8s receiver, operating at a frequency of 1 Hz and tracking signals from GPS, GLONASS, and Galileo constellations in dual-frequency mode. Processing was performed with the open-source software RTKLIB (Takasu et al., 2007; Takasu, 2009), employing the static positioning method. In particular, the Post-Processing Kinematic (PPK) approach was adopted—an alternative to real-time

kinematic (RTK) positioning—in which corrections are applied during post-processing using data from the nearest permanent station (CUEC), along with precise satellite ephemerides (available every 15 days), satellite clock corrections, and ionospheric and tropospheric models.

The monitoring program was initiated in 2017 following the acquisition of Trimble R8s receivers. Initial tests with RTK positioning (2 min intervals) proved unsatisfactory due to horizontal and vertical uncertainties exceeding 1 cm. To improve accuracy, the methodology was progressively refined, moving first to 30 min static sessions and later to 1-hour fast-static sessions per point, with strict forced-centering to ensure reproducibility. These adjustments enabled the generation of reliable time series capturing the evolution of surface displacement vectors (Khalili et al., 2023).

The GNSS receivers tracked the GPS (Global Positioning System), GLONASS (GLObal NAVigation Satellite System), and Galileo constellations, acquiring L1 and L2 frequency signals. For this study, data collected between July 2021 and June 2024 at the 28 observation points were analyzed, with a sampling rate of 1 Hz and monthly measurement campaigns.

4. Results

After performing the GNSS and interferometric data analyses according to the procedures described in the chapter “*Data Processing Methodology*”, the results concerning the active deformations in the study areas during the considered time spans were obtained. In the following sections, the outcomes for the two case studies described above are presented.

4.1 Fiastra DSGSD

From the GPS data processed in PPK mode using the RTKLib software, as previously described, three-dimensional surface deformation time series were obtained.

The rover STA1 (Fig. 4.1.1) shows a relatively stable trend in the pre- and post-earthquake periods; however, the most evident displacements are associated with the Norcia earthquake. Specifically, during this event, deformations of approximately 25 mm westward, 100 mm northward, and a subsidence of about 50 mm were recorded.

For the rover STA2 (Fig. 4.1.2), the east–west component shows a shift of about 20 mm westward during the two October 2016 events and approximately 100 mm westward during the January 2017 earthquake. In the north–south component, a displacement of about 60 mm southward was observed during the January 2017 event, while in the up–down component downward shifts of 10–20 mm occurred during the two October 2016 events.

The rover STA3 (Fig. 4.1.3) recorded a shift of approximately 5 mm eastward in the east–west direction during the two October 2016 earthquakes; a northward displacement of about 15 mm in the north–south component during the January 2017 event; and an upward movement of around 10 mm in the up–down direction during the same January 2017 earthquake. In this case, the most significant deformations are associated with the Accumoli earthquake. The GPS network also experienced several issues during the seismic sequence: the reference station STA4 was displaced as a consequence of ground deformation;

during the earthquakes of January 18, 2017, the GPS stations were buried by snow and stopped transmitting for one week; STA2 suffered from a transmission failure, resuming operation only after a site visit on March 24, 2017.

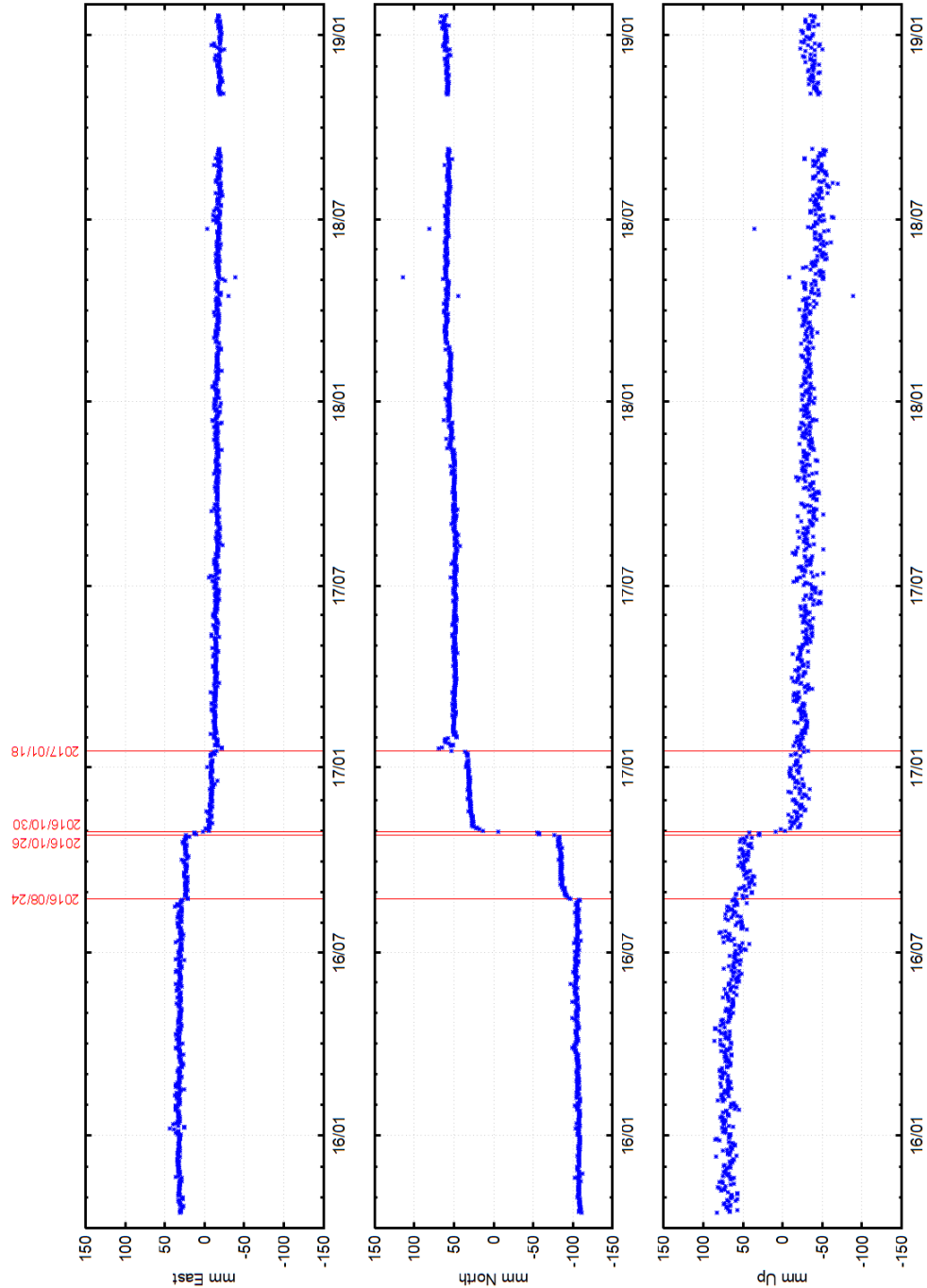


Figure 4.1.1: Time series of the GPS STA1. Vertical red lines indicate the main events of the 2016–2017 Central Italy seismic sequence.

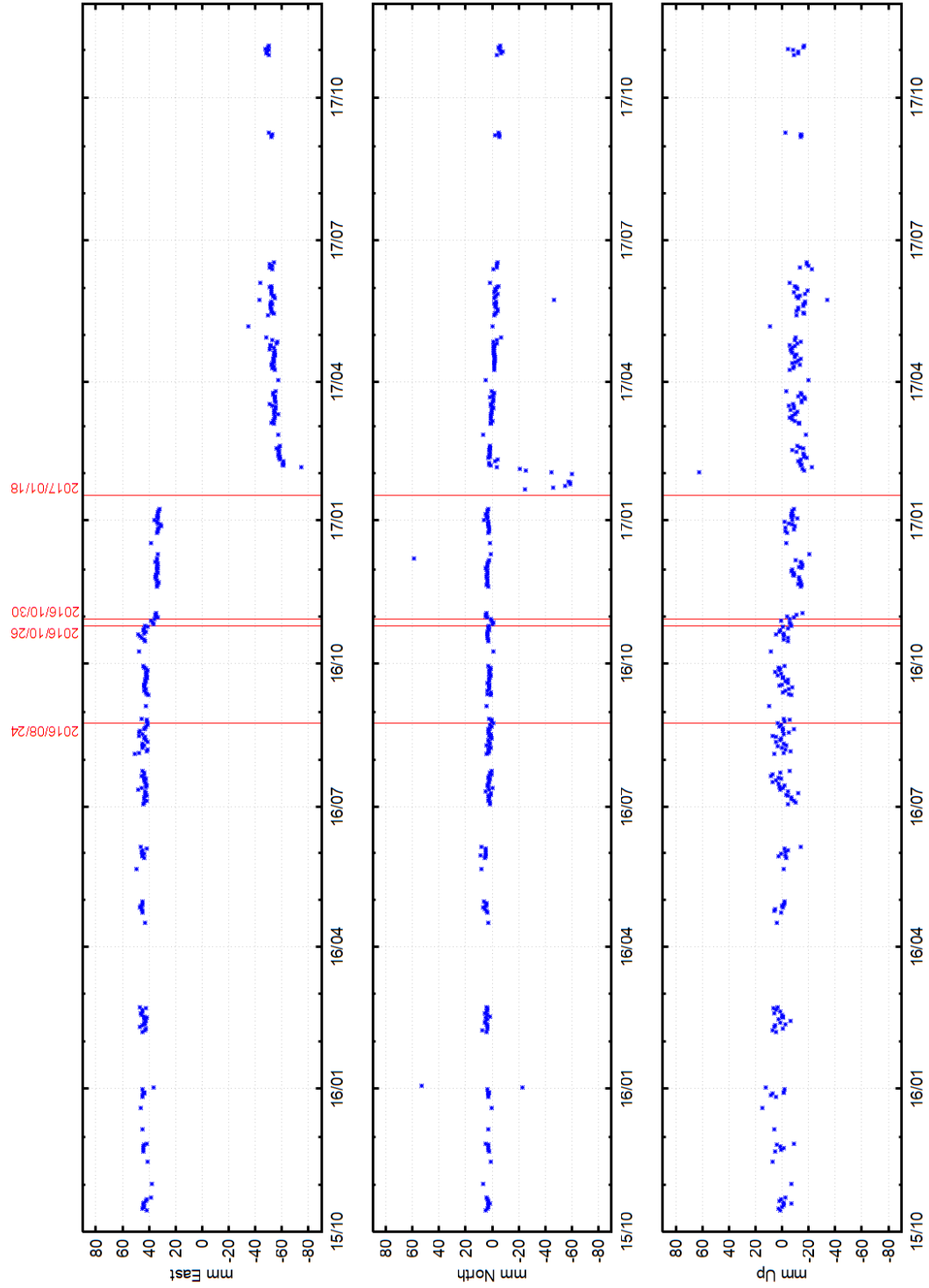


Figure 4.1.2: Time series of the GPS STA2. Vertical red lines indicate the main events of the 2016–2017 Central Italy seismic sequence.

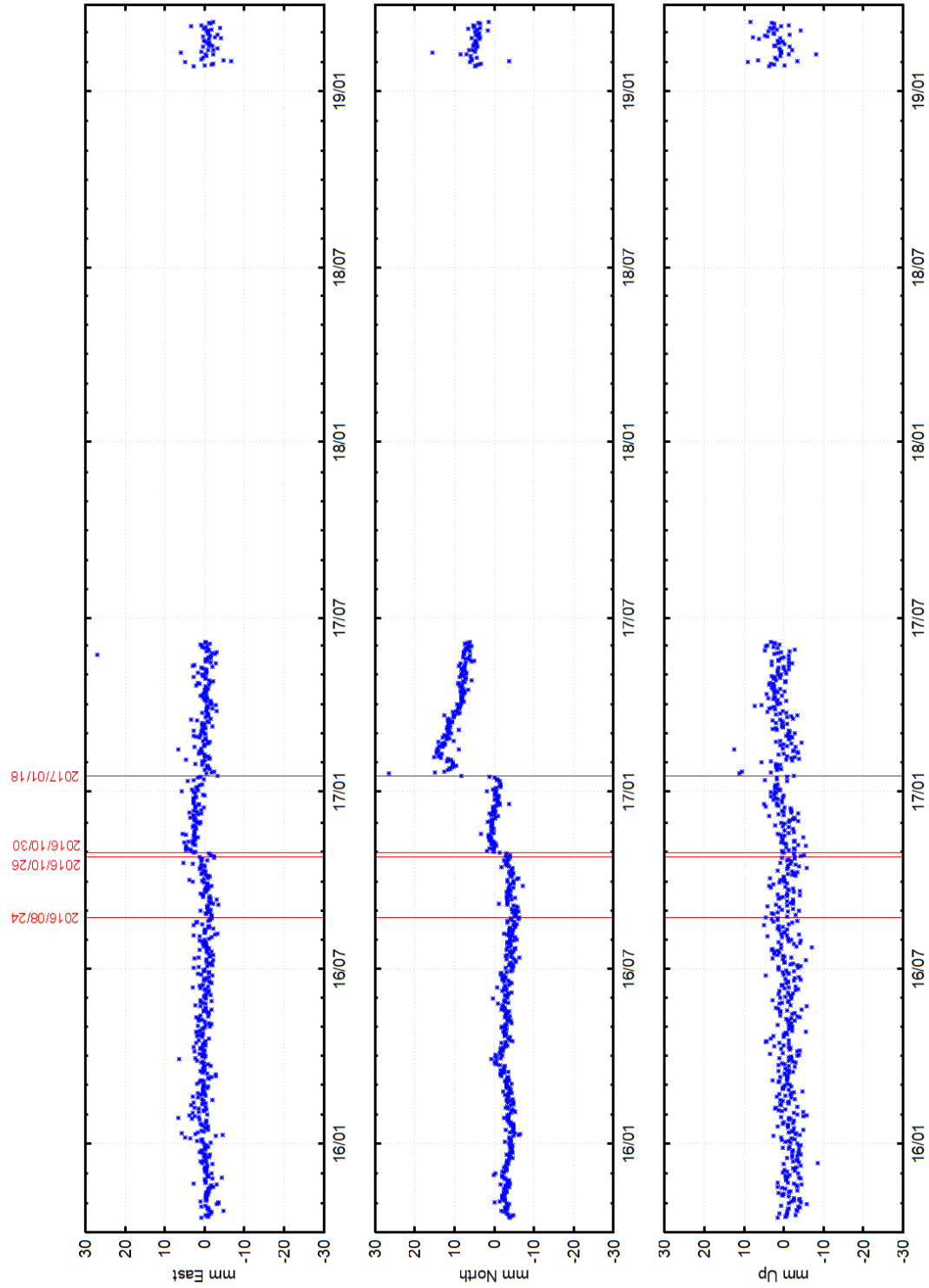


Figure 4.1.3: Time series of the GPS STA3. Vertical red lines indicate the main events of the 2016–2017 Central Italy seismic sequence.

Based on interferometric data retrieved from the EGMS platform, which provides Sentinel-1 acquisitions in both ascending and descending orbital geometries, maps of the average displacement rate along the Line of Sight (LoS) were generated for the identified targets. By combining ascending and descending datasets and applying the methodology described in the section on interferometric data processing, it was possible to decompose the LoS velocities into their directional components (Fig. 4.1.4). Due to the nearly north–south orientation of Sentinel-1 orbits, the decomposition is limited to the *horizontal* (*east–west*) and *vertical* (*up–down*) directions. The horizontal component, aligned with the x-axis (E–W), shows maximum rates of -6.82 mm/yr (westward) and up to $+14.2$ mm/yr (eastward), while the vertical component (z-axis) records maximum uplift of $+6.27$ mm/yr and subsidence of -13.12 mm/yr. To enable direct comparison with the GPS time series, displacements were decomposed into *east–west* and *up–down* components. For each GPS rover, one Persistent Scatterer (PS) in ascending geometry and one in descending geometry were selected within the surrounding area. By applying equations based on ascending and descending displacements and the radar incidence angle, the two directional components were obtained and subsequently used to derive displacement time series.

The time series of the selected PSs, located in proximity to the GPS stations, are presented below. Vertical red lines in the graphs indicate the earthquakes that occurred during the 2016–2017 Central Italy seismic sequence, facilitating the interpretation of surface deformations induced by seismic shaking and highlighting short-term accelerations or variations in displacement trends related to tectonic activity. In particular:

For the PSs near STA1 (Fig. 4.1.5), in the *east–west* component, the most significant deformations occurred during the October 2016 earthquakes, reaching about 15 mm; in the *up–down* component, downward movements of approximately 5–10 mm were detected during the same events.

For the PSs close to STA2 (Fig. 4.1.6), the *east–west* component indicates approximately 40 mm of eastward deformation during the October 2016 earthquakes, while in the *up–down* component around 10 mm of subsidence occurred during the same events.

For the PSs near STA3 (Fig. 4.1.7), the *east–west* component shows about 20 mm of eastward deformation during the October 2016 earthquakes, while the *up–down* component indicates subsidence of approximately 10 mm during those events.

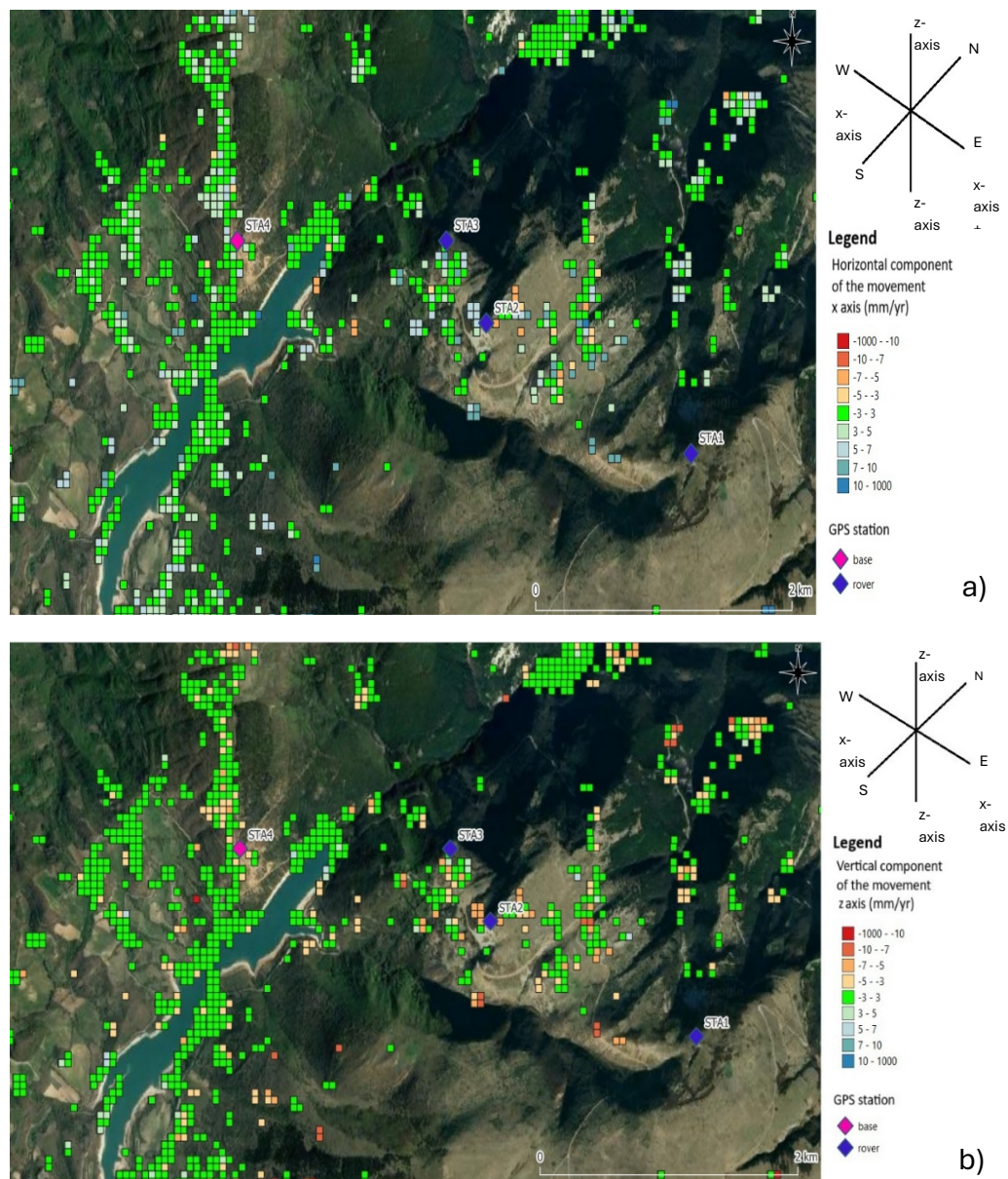


Figure 4.1.4: a) Horizontal component of the mean displacement rate; b) Vertical component of the mean displacement rate.

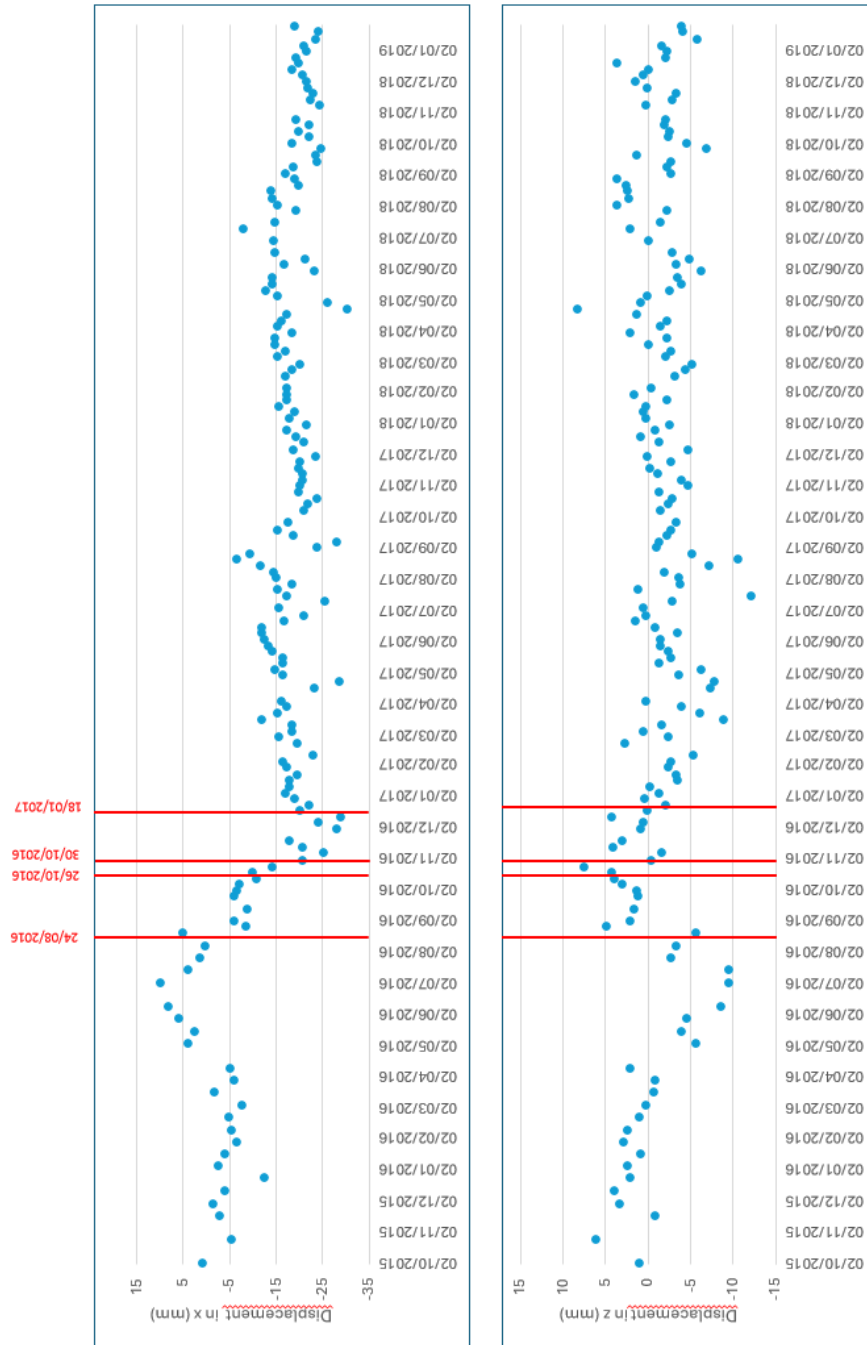


Figure 4.1.5: Time series of displacements in the east–west (left) and up–down (right) components for Persistent Scatterers (PS) located near GPS station STA1. Vertical red lines indicate the main seismic events of the 2016–2017 Central Italy seismic sequence.

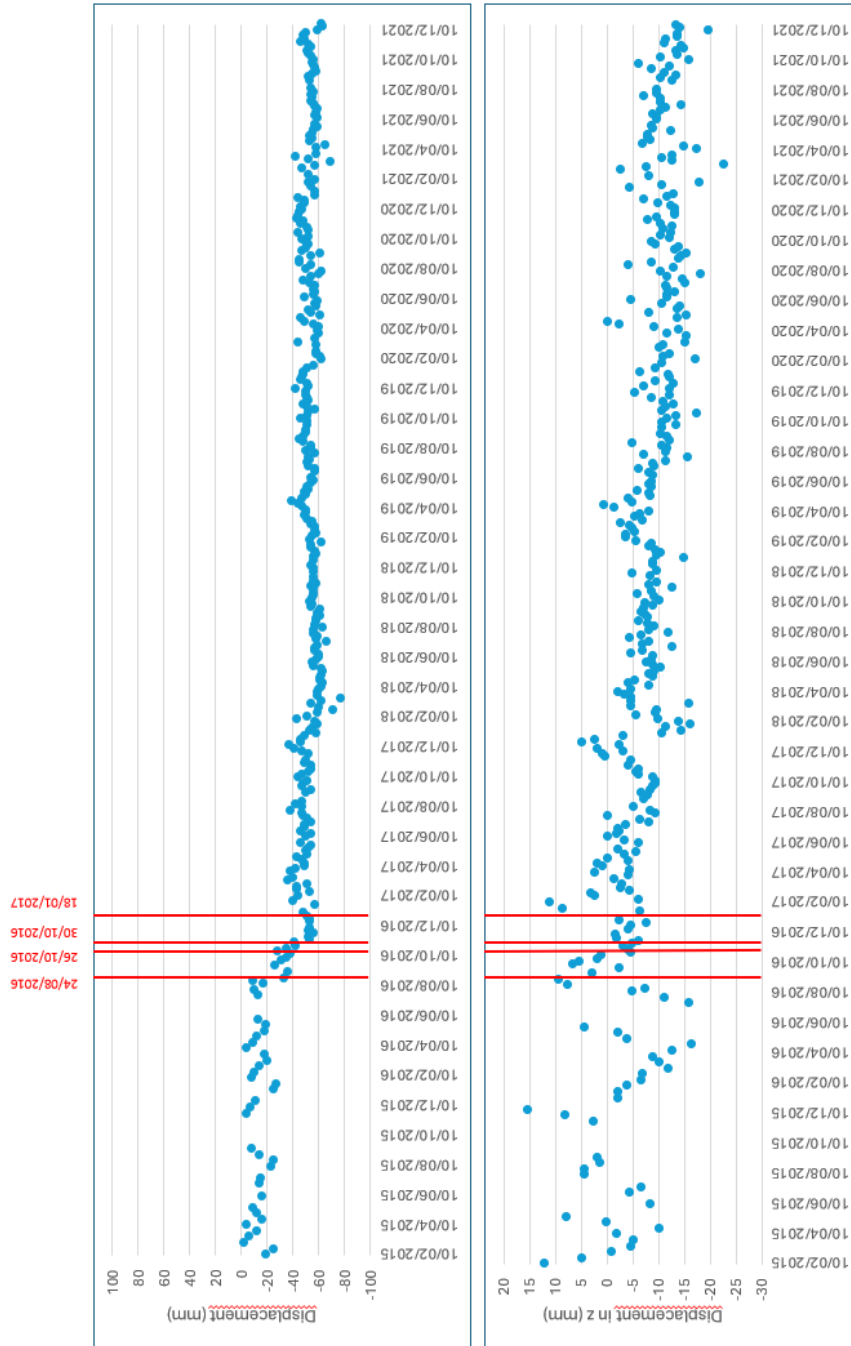


Figure 4.1.6: Time series of displacements in the east–west (left) and up–down (right) components for Persistent Scatterers (PS) located near GPS station STA2. Vertical red lines indicate the main seismic events of the 2016–2017 Central Italy seismic sequence.

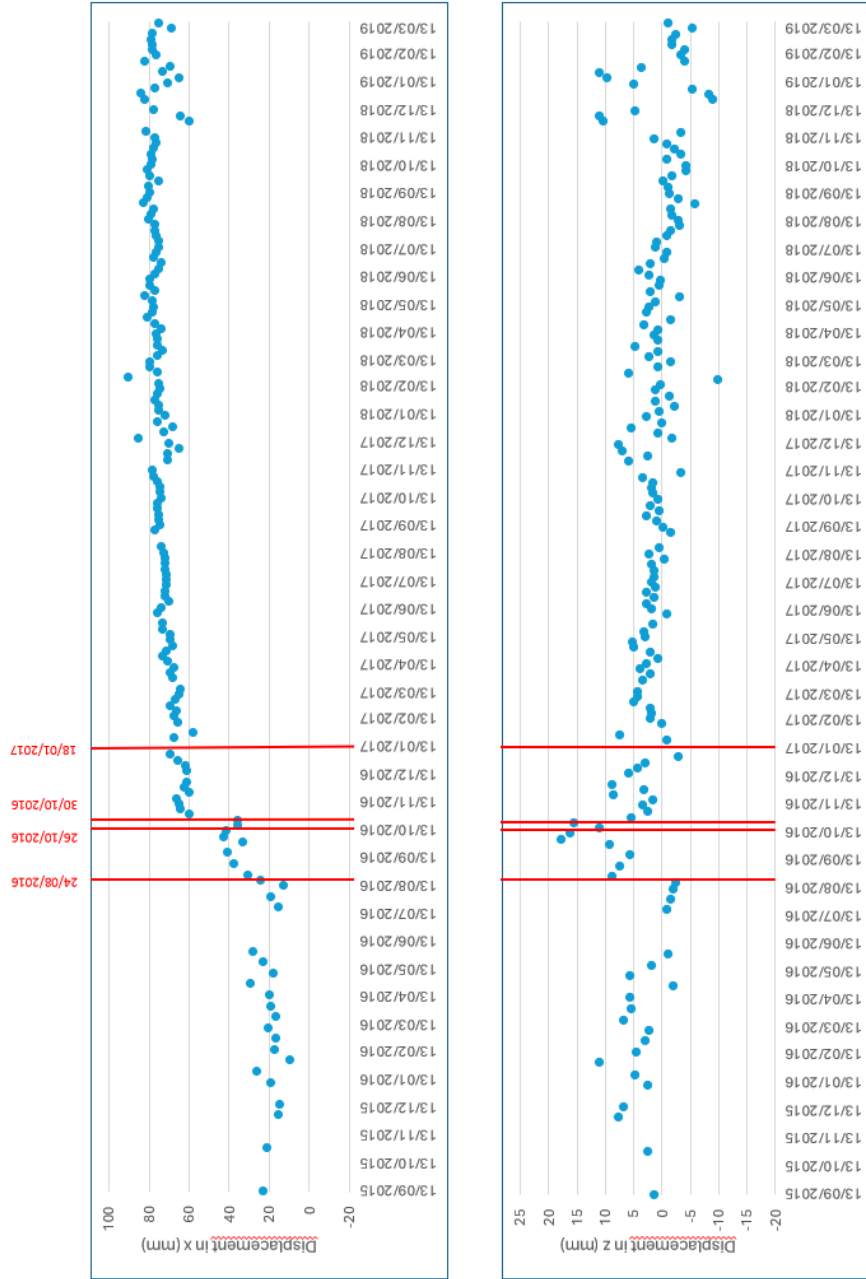


Figure 4.1.7: Time series of displacements in the east–west (left) and up–down (right) components for Persistent Scatterers (PS) located near GPS station STA3. Vertical red lines indicate the main seismic events of the 2016–2017 Central Italy seismic sequence.

4.2 Cuenca landslide

The GNSS analysis, performed in PPK on the geodetic monitoring network consisting of 28 markers installed around the University of Azuay campus, enabled the generation of displacement time series. In particular, the results of nine markers—selected as the most representative—are presented here. Among these, four are located outside the landslide contour, while five fall within the unstable area (Fig. 4.2.1).

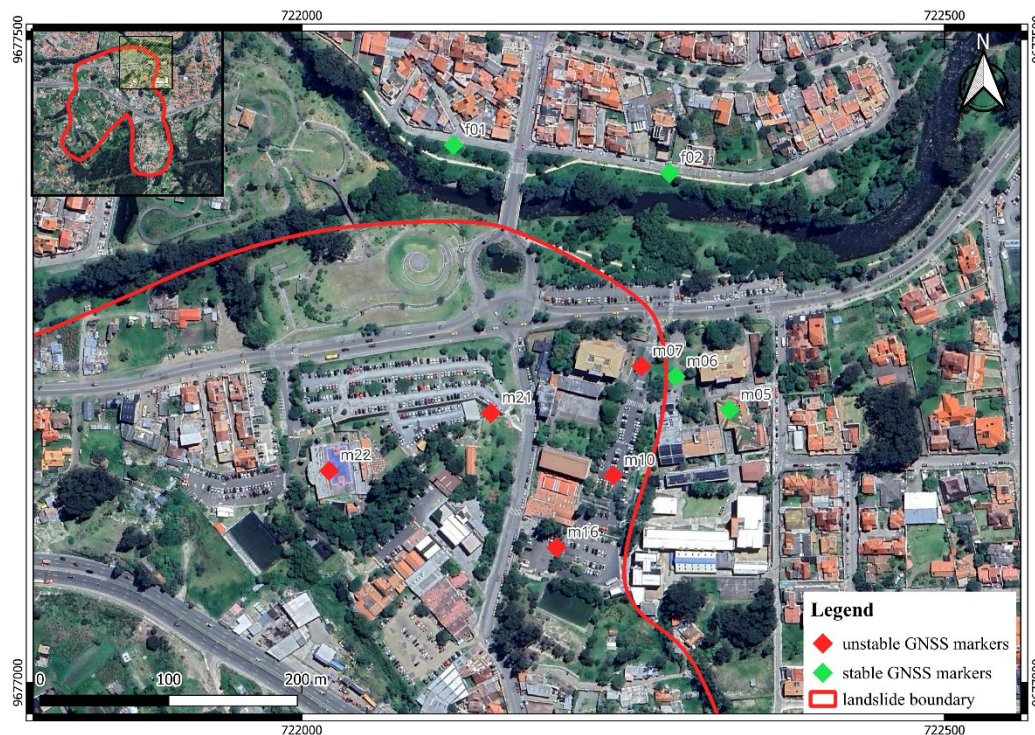


Figure 4.2.1: Distribution of the nine GNSS markers selected for landslide monitoring. The boundaries of the unstable area are outlined on the map. Markers within the landslide body (in red) show unstable behavior, whereas those outside the affected area (in green) are stable.

The results consist of three-dimensional displacement time series (East–West, North–South, and vertical components). Below is shown the displacements of the nine markers. Of these, four (green points) are considered stable, as they are located outside the landslide body, whereas the remaining five (red points), located within the unstable sector, are expected to exhibit significant displacements. The time series of displacement is illustrated in the images below (Figs. 4.2.2, 4.2.3).

As expected, no appreciable ground deformation is observed in any of the three spatial components for markers f01, f02, m05, and m06, which lie outside the landslide zone. In contrast, the internal markers exhibit marked displacements toward the north, with cumulative values reaching up to ~22 cm over slightly more than two years. Moreover, all markers inside the unstable area show systematic eastward movements, with cumulative displacements of approximately 10 cm.

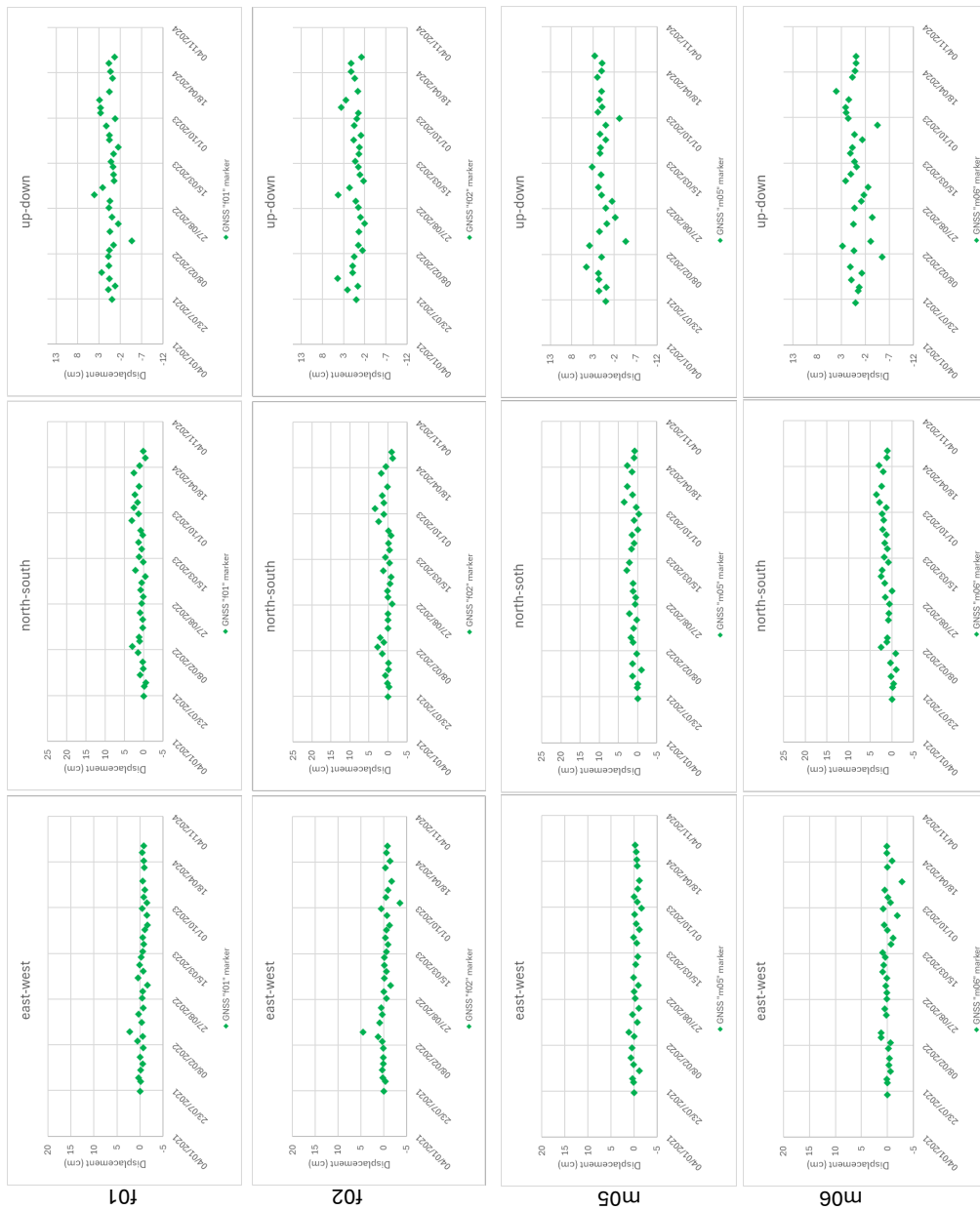


Figure 4.2.2: Time series of displacements recorded by the stable GNSS markers located outside the landslide area, shown in the three spatial components: east-west, north-south, and vertical (up-down).

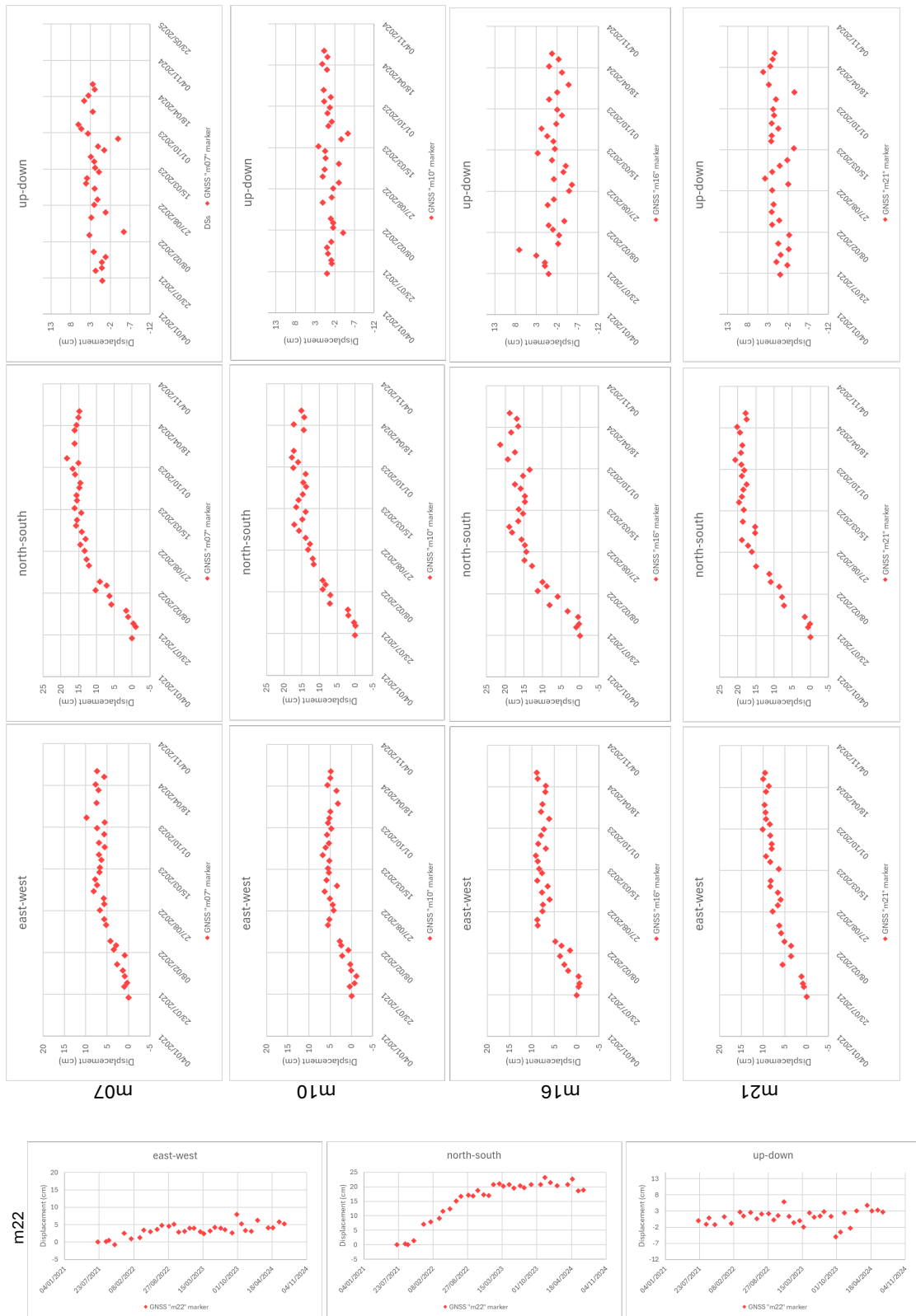


Figure 4.2.3: Time series of displacements recorded by the unstable GNSS markers located outside the landslide area, shown in the three spatial components: east-west, north-south, and vertical (up-down).

Through the Small BAseline Subset (SBAS) approach of the Multi-Temporal InSAR (MT-InSAR) technique applied to interferometric data acquired by the Sentinel-1A satellite, mean displacement rate maps were generated for both ascending and descending orbits. The displacement rates obtained highlight a slow kinematic behavior. In particular, the data from the ascending orbit (Fig. 4.2.4) show maximum velocities of -1.53 cm/year, located in the central sector of the landslide body, with significant concentrations in correspondence with the buildings of the university campus. As for the descending orbit (Fig. 4.2.5), the maximum velocities reach -1.26 cm/year in the same central area, while displacement rates up to 1.11 cm/year were detected along the toe of the phenomenon.

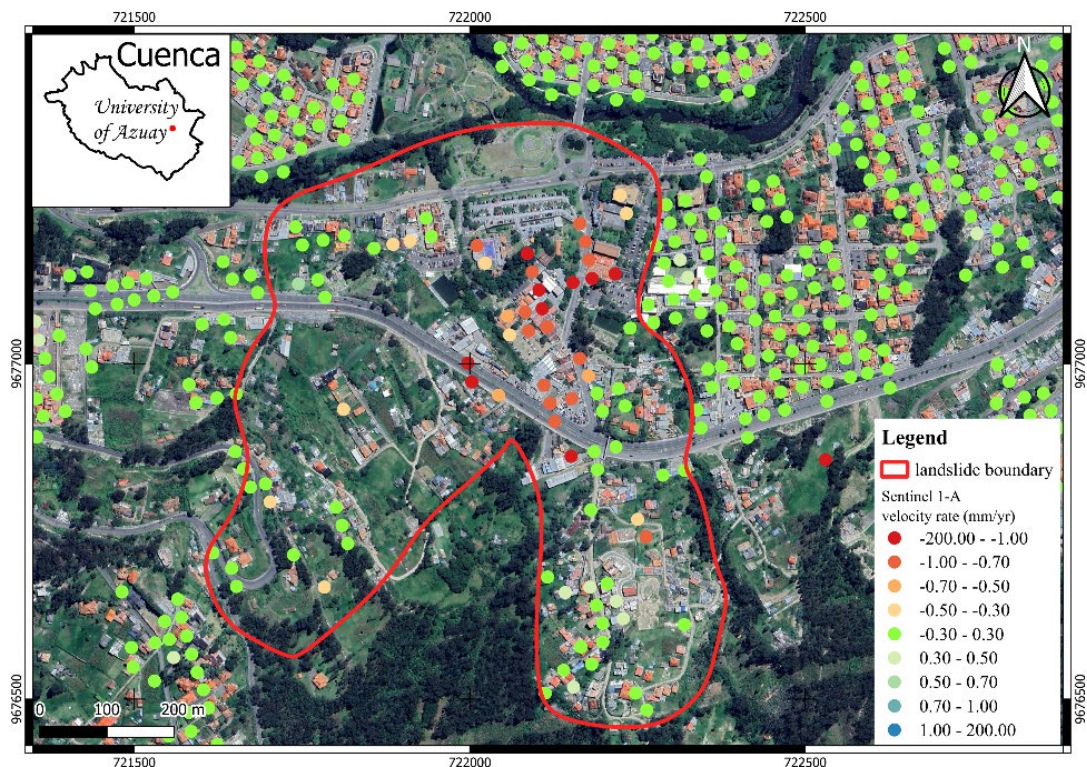


Figure 4.2.4: Mean displacement rate map in ascending orbit.

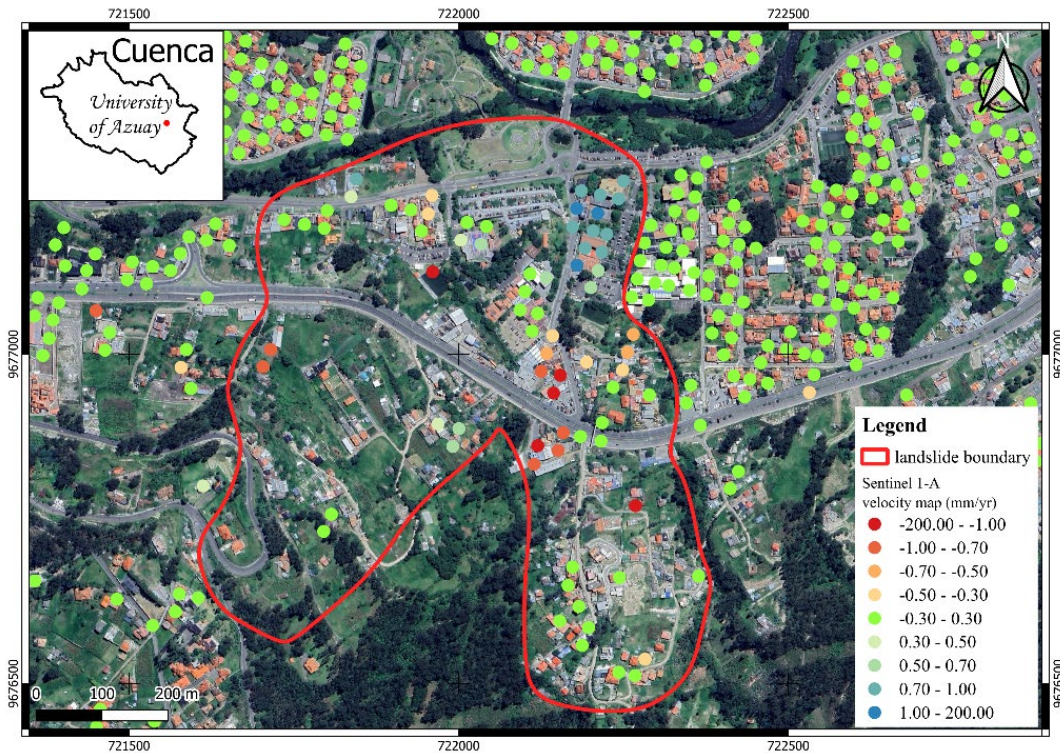


Figure 4.2.5: Mean displacement rate map in descending orbit.

By applying the methodology described in the previous paragraph, the displacements detected along the Line of Sight (LoS), in both ascending and descending geometries, were decomposed into East–West and Up–Down components (Khalili et al., 2023). These are cumulative displacements, with the initial value set to zero starting from the first day of data acquisition. For each GNSS marker, the corresponding Distributed Scatterers (DS) from both geometries were identified in proximity (Fig. 4.2.6), and their cumulative displacements were computed to reconstruct the associated time series.

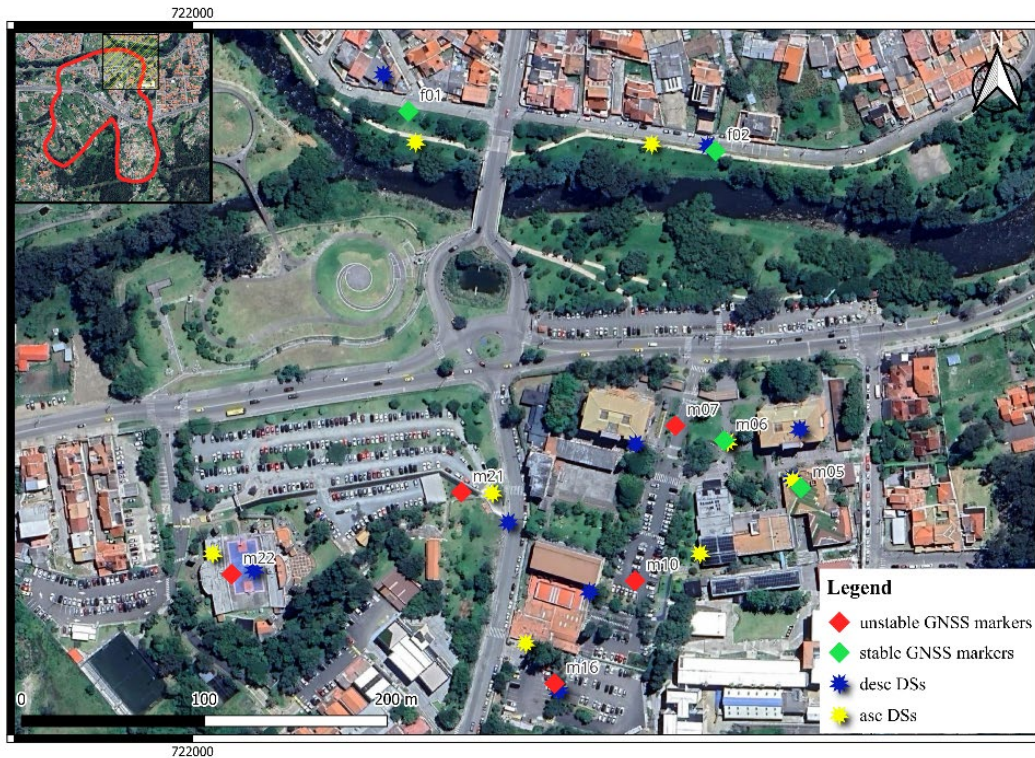


Figure 4.2.6: Location of the GNSS markers and the corresponding Distributed Scatterers (DS) identified in both ascending and descending geometries. The DS were selected in close proximity to each marker for the reconstruction of cumulative time series, obtained by decomposing the Line of Sight (LoS) displacements into East–West and vertical (Up–Down) components.

Although this analysis was carried out for all available points, only the most representative cases are presented here. Specifically, Figures 4.2.7 and 4.2.8 show respectively four time series for stable points in blue, located in the eastern portion outside the landslide body, and five time series for unstable points in orange, situated in the north-eastern sector of the landslide area. For the latter, displacements up to 8 cm eastward were observed (DS corresponding to markers m07, m16, and m21), along with a maximum vertical subsidence of approximately 2 cm (marker m10).



Figure 4.2.7: Time series of the stable Distributed Scatterers (DS), shown in the East–West and vertical (Up–Down) directions. These DS were used for the decomposition of the displacement detected along the satellite Line of Sight (LoS) in both ascending and descending geometries.



Figure 4.2.8: Time series of the unstable Distributed Scatterers (DS), shown in the East–West and vertical (Up–Down) directions. These DS were used for the decomposition of the displacement detected along the satellite Line of Sight (LoS) in both ascending and descending geometries.

To obtain an accurate assessment of the consistency between the results derived from the two different analysis methodologies, GNSS and SBAS, the previously analyzed time series were overlaid in a single graph to facilitate direct comparison. The figure 4.2.9 clearly illustrates the trend of the displacements detected over time using both techniques, thereby highlighting any similarities or discrepancies between the two measurements. A visual inspection of the time series reveals an excellent agreement between the data acquired through GNSS measurements and those obtained from SBAS processing.

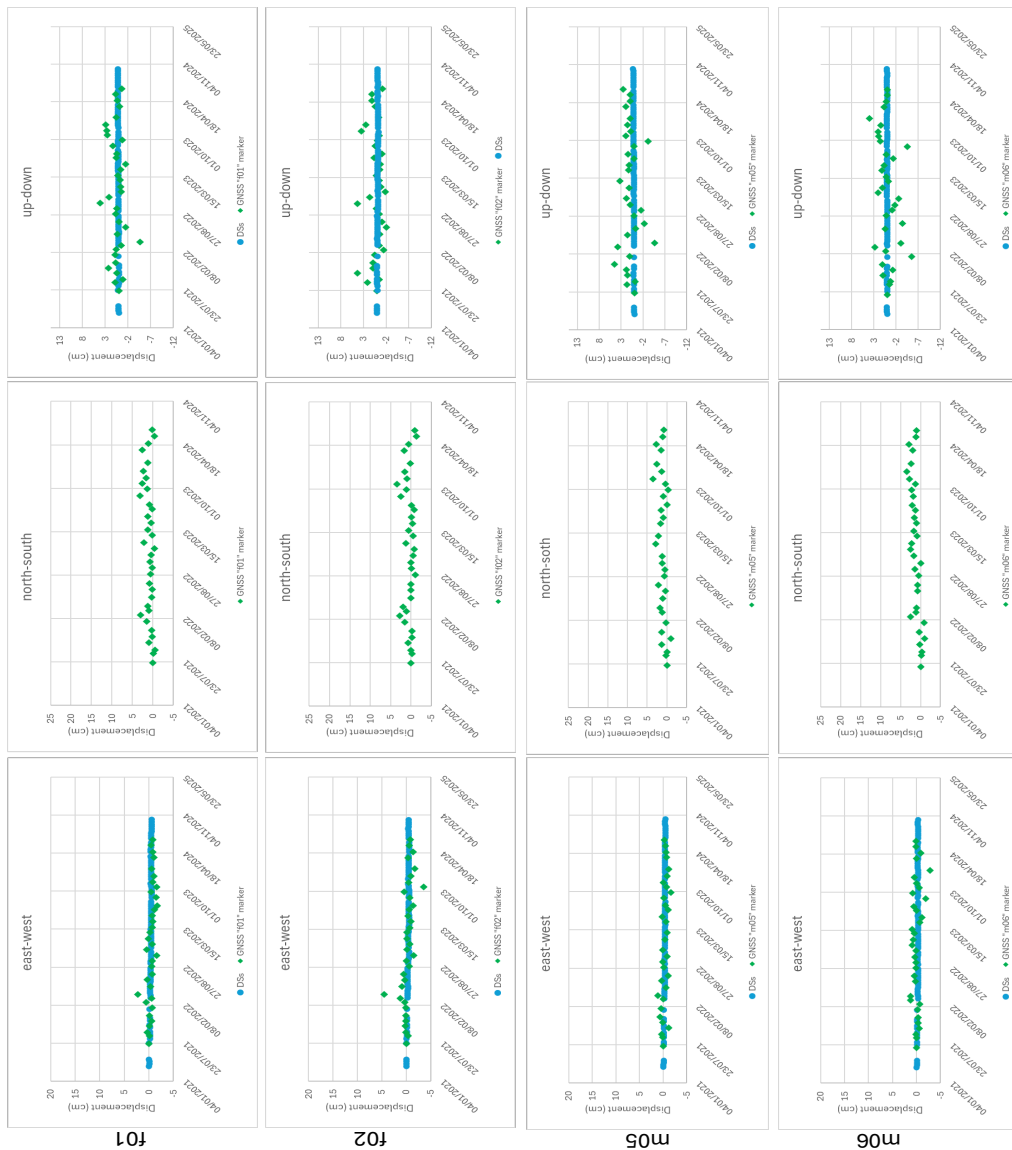




Figure 4.2.9: Comparison of displacement time series from DS-InSAR and GNSS data. Stable points are shown in green (GNSS) and light blue (DS), while unstable ones are shown in red (GNSS) and orange (DS).

5. Discussion

The results obtained from the combined use of GNSS and InSAR techniques provide a comprehensive and multi-dimensional understanding of the deformation processes affecting the study areas (Fiastra DSGSD and Cuenca landslide). For this study, GNSS data were processed using the Post-Processing Kinematic (PPK) method through the open-source RTKLib software, a strategic choice that ensured the millimetric accuracy required. PPK proved particularly advantageous compared to Real-Time Kinematic (RTK) for its robustness and ability to mitigate communication interruptions, and it was more suitable than Precise Point Positioning (PPP) for the short baselines typical of local monitoring. InSAR data were processed to obtain surface displacements along the Line-of-Sight (LoS), which were then decomposed into East–West and vertical (Up–Down) components using multiple satellite geometries (ascending and descending) and applying the methodology of Khalili et al. (2023), essential to obtain a complete two-dimensional kinematic reconstruction of the movements. GNSS delivers precise, three-dimensional measurements at discrete points, particularly effective for detecting rapid or co-seismic ground movements, while InSAR offers spatially continuous information on surface displacements with millimeter accuracy over wide areas. The integration of these approaches allows for a more accurate separation of vertical and horizontal components of ground motion, overcoming the intrinsic limitations of each technique when applied independently. This joint perspective is fundamental for interpreting landslide kinematics and their temporal and spatial evolution.

For the Fiastra DSGSD, the GPS analysis highlights significant co-seismic displacements associated with the 2016–2017 Central Italy seismic sequence. The three monitored stations show heterogeneous responses: STA1 records the largest deformation during the Norcia earthquake (October 2016), while STA2 and STA3 exhibit displacements more clearly linked to the January 2017 events (Figs. 4.1.1 - 4.1.3). These observations emphasize the strong sensitivity of

GNSS instruments in capturing rapid, impulsive ground movements induced by seismic shaking, with three-dimensional measurements allowing detailed reconstruction of both horizontal and vertical components.

These results are broadly consistent with those presented by Amato et al. (2018), who, using a partially overlapping GPS network, also highlighted the major seismic events of October 2016 (Norcia) and January 2017 as the primary triggers for ground displacements. In particular, both studies indicate that the STA1 station exhibited the most pronounced movements, generally oriented toward the northwest/west with associated subsidence. Similarly, the movements observed at STA2 align with the post-seismic trends reported by Amato et al. (2018), taking into account that environmental factors, such as snow or adverse weather conditions, may have influenced the measurements. Another important aspect to consider is the choice of software for GPS data processing, which may influence the analysis approach and workflow. Amato et al. (2018) employed a combination of NDA-Lite (for single-frequency data) and BERNESSE (for dual-frequency data), which are proprietary solutions with built-in processing models and filters. In contrast, our analysis relied entirely on RTKLib, an open-source software that offers full transparency of processing algorithms, high flexibility in defining parameters, and no licensing costs. These features allow for detailed customization and adjustments in the processing workflow, ensuring that, even if minor differences arise, the overall deformation patterns remain consistent.

The interferometric analysis provides complementary insights. The mean velocity maps derived from Sentinel-1 ascending and descending acquisitions (Fig. 4.1.4) indicate persistent deformation trends, with rates of several mm/yr in both horizontal and vertical directions. Once decomposed into east–west and up–down components, the time series of selected Persistent Scatterers (PS) in proximity to the GPS stations reveal deformation patterns consistent with the GNSS observations (Figs. 4.1.5 – 4.1.7). In particular, both techniques detect west–east shifts and episodes of subsidence temporally coincident with the

major earthquakes of October 2016 and January 2017. Nevertheless, differences between the datasets are evident. GNSS captures abrupt, co-seismic offsets with centimeter-level precision, while InSAR, due to its acquisition frequency and sensitivity to decorrelation, tends to smooth or underestimate rapid displacements. This explains why InSAR-derived time series show cumulative deformations comparable to GPS trends but fail to fully resolve the instantaneous “jumps” recorded by GNSS during seismic events. This underestimation is a common limitation, also confirmed by Amato et al. (2018) in the comparison between their InSAR data (CSK and Sentinel-1) and the point-based GPS measurements. On the other hand, InSAR provides broader spatial coverage, enabling the identification of deformation patterns across the entire slope, which is not possible with the point-based GNSS approach.

For the Cuenca landslide, the interferometric data, represented in the average velocity maps shown in Figures 4.2.4 (ascending) and 4.2.5 (descending), highlight a slow kinematic behavior, with maximum LoS velocities in the central sector, strongly corresponding to the areas of the University campus. Moreover, the maps clearly delineate the boundaries of the landslide-affected area poichè all moving DS (Distributed Scatterers) are located within the area previously defined as a landslide. Furthermore, the spatial resolution and the sensitivity of the deformation velocity measurements allow for the identification of two distinct deformation phenomena within the landslide body. This differentiation is based on both the different deformation rates observed in the two sectors and the differing displacement directions characterizing each portion of the slope.

Specifically, a significant uplift is observed in the toe area of the landslide, which can be interpreted as the result of the convergence of material coming from both unstable sectors, leading to an accumulation and upward movement of the mass at the base of the slope. This observation is crucial for interpreting the instability as a slow translational/rotational landslide mechanism. This interpretation is strongly supported by the complementary study of Khalili et al.

(2024), who, employing a synergistic multi-sensor approach (Sentinel-1A SBAS and CSK PSI), also confirmed the existence of two distinct deformation phenomena and the presence of a clear accumulation zone (Area D in their study) at the toe, where the convergence of the volumes generated significant uplift values.

The analysis of time series, in which LoS displacements were decomposed into East–West and Up–Down components, enabled the quantification of deformations occurring between 2021 and 2024. However, it is not possible to detect displacement along the North–South direction due to the semipolar configuration of the satellite orbits, which move precisely in that direction: as a result, displacements occurring along the satellite’s direction of motion cannot be detected. In this context, the GNSS analysis is revealed to be complementary and fundamental. The GNSS time series show significant cumulative deformations in the North direction, demonstrating the diagnostic importance of GNSS for the kinematics of movement in that direction, which is largely invisible to InSAR. The convergence between our analysis and the synergistic approach of Khalili et al. (2024) is significant, especially regarding the spatial patterns and the identified structural complexity. This illustrates that while our methodology provided essential 3D kinematic components, multi-sensor synergy, leveraging the high resolution of CSK, is key to optimizing the spatial delineation and overall quality of satellite-derived deformation rates. The methods reveal a good agreement in the deformation components between GNSS and InSAR results. Nevertheless, some differences have been observed, related to the specific characteristics of each technique. Sentinel-1A shows limited sensitivity in detecting rapid deformations, a limitation also found in the Fiastra case, and an underestimation of displacements compared to GNSS. This is evident in the deformation graphs shown in Figure 4.2.9 for markers M10, M16, and M22, where the East–West deformation detected through interferometry is lower than that recorded by GNSS. This represents one of the main limitations of interferometry. On the other hand, regarding the vertical

component, GNSS instruments exhibit greater sensitivity, although they are also more affected by instrumental and environmental noise. This results in time series that are generally more scattered, making the precise interpretation of vertical deformation signals more challenging.

6. Conclusions

The integration of GNSS and interferometric data enabled a detailed three-dimensional reconstruction of the deformation processes affecting both study areas. The results confirm the effectiveness of a multi-technique approach in monitoring slow-moving landslides and DSGSDs, demonstrating how the complementarity of GNSS and InSAR overcomes the intrinsic limitations of each individual method. An additional methodological strength of our work is the reliance on the open-source software RTKLib for GNSS data processing, which ensures high transparency and reproducibility of the results.

For the Fiastra DSGSD, the combined analysis of GPS and DInSAR proved particularly effective for investigating deep-seated gravitational phenomena, especially in relation to the 2016–2017 seismic sequence. GPS measurements highlighted rapid, co-seismic displacements with centimeter-level accuracy, while InSAR provided continuous spatial coverage of deformation patterns, revealing persistent post-seismic and inter-seismic trends. Despite the intrinsic differences—point-based precision versus wide-area coverage—the two datasets show good agreement, demonstrating that their integration provides a reliable tool for capturing both the impulsive dynamics induced by seismic events and the longer-term slope readjustments. These findings confirm that the joint use of GNSS and InSAR is not only suitable for monitoring seismic-induced landslide activity but also essential for understanding the spatial variability of slope responses to external forcing.

For the Cuenca landslide, the observed movement corresponds to a slow, translational/rotational landslide, distinguished by two distinct deformation phenomena, with accumulation zones evident near the toe of the slope, adjacent to the Yanuncay River. GNSS analysis, based on discrete monthly measurements carried out on a network of 25 DGPS markers, enabled the reconstruction of time series in three spatial components, revealing cumulative deformations exceeding 20 cm in the north direction and 10 cm eastward. This resolution of the North-South component by GNSS was essential, considering

the inability of SAR satellites to observe deformations along that direction. In parallel, SAR data processed using the SBAS technique applied to Sentinel-1A images in both ascending and descending geometries revealed displacement velocities up to -1.5 cm/year in the central sector of the landslide, with an accumulation area at its toe. The decomposition of Line-of-Sight (LOS) measurements allowed the separation of vertical and horizontal (east–west) components, making a direct comparison with GNSS data possible. This comparison demonstrated good consistency between the two techniques in the measurable components, with slight discrepancies due to the specific sensitivities and limitations of each method.

The use of long-duration DGPS campaigns and forced-centering baselines significantly reduced morphological, anthropogenic, and instrumental errors, enabling millimetric detection of ground deformation. As a result, the DGPS network currently represents a reliable diagnostic and early-warning tool for the instability affecting the university campus and surrounding infrastructure. In addition to these activities, a permanent GNSS monitoring network is being developed, consisting of four rover receivers installed within the landslide body and one reference base station outside the unstable area. The system, based on Leica GRX1200+ receivers with Leica AT504 geodetic antennas, is supported by the collaboration between the University of Naples Federico II, the University of Azuay, and the Irpinia Section of the National Institute of Geophysics and Volcanology (INGV). A real-time data analysis program has also been designed, capable of automatically retrieving data from the stations, applying corrections, and generating real-time displacement time series. An alert function issues warnings when predefined displacement thresholds are exceeded—an essential step toward the implementation of an effective early warning system that benefits both the population and local infrastructure. Overall, the results not only improve the understanding of the mechanical behavior of the unstable slopes but also confirm the value of the integrated GNSS–InSAR approach for monitoring active landslides in complex contexts.

The high-resolution spatial and temporal information provides critical support for land-use planning, infrastructure maintenance, and risk mitigation strategies. The reliability and precision of the interferometric analysis results represent an added value for ensuring the safety of local populations and the long-term sustainability of human activities in the affected areas.

References

- Agliardi, F., Crosta, G., & Zanchi, A. (2001). Structural constraints on deep-seated slope deformation kinematics. *Engineering Geology*, 59(1–2), 83–102.
- Albano, M., Polcari, M., Moro, M., Bignami, C., Lombardini, F., Viviani, F., Samsonov, S., Saroli, M., Devoti, R., & Stramondo, S. (2015). COSMO-SkyMed and Radarsat-2 joint analysis and modeling for the evaluation of potential deformations caused by the large mass movements surrounding the Fiastra lake dam. *Geoscience and Remote Sensing Symposium (IGARSS)*, 2015.
- Amato, G., Devoti, R., Fubelli, G., Aringoli, D., Bignami, C., Galvani, A., Moro, M., Polcari, M., Saroli, M., Sepe, V., & others. (2018). Step-like displacements of a deep seated gravitational slope deformation observed during the 2016–2017 seismic events in Central Italy. *Engineering Geology*, 246, 337–348.
- Aringoli, D., Gentili, B., Materazzi, M., Pambianchi, G., & others. (2010). Mass movements in Adriatic Central Italy: Activation and evolutive control factors. *Landslides: Causes, types and effects*, 1–71.
- Ashkenazi, V., & Cross, P. (1976a). Strength of long lines in terrestrial geodetic control networks. *Bulletin géodésique*, 50(2), 169–180.
- Ashkenazi, V., & Cross, P. (1976b). Strength of long lines in terrestrial geodetic control networks. *Bulletin géodésique*, 50(2), 169–180.

- Baldock, J. (1982). Geología del Ecuador. *Boletín de Explicación del Mapa geológico de la República del Ecuador. Dirección General de Geología y Minas, Quito*, 70.
- Bates, R. L., & Jackson, J. A. (1987). *Glossary of geology*.
- Berardino, P., Fornaro, G., Lanari, R., & Sansosti, E. (2002). A new algorithm for surface deformation monitoring based on small baseline differential SAR interferograms. *IEEE Transactions on geoscience and remote sensing*, 40(11), 2375–2383.
- Blanco-Sanchez, P., Mallorquí, J. J., Duque, S., & Monells, D. (2008). The coherent pixels technique (CPT): An advanced DInSAR technique for nonlinear deformation monitoring. *Pure and applied geophysics*, 165(6), 1167–1193.
- Bristow, C., & Guevara, S. (1980). Mapa geológico de la Hoja Azogues (1: 100,000). *Dirección General de Geología y Minas, Quito*.
- Bristow, C. R. (1973). *Guide to the geology of the Cuenca Basin, southern Ecuador*. Ecuadorian Geological and Geophysical Society.
- Bristow, C. R., & Hoffstetter, R. (1977). *Lexique Stratigraphique International*.
- Calamita, F., Cello, G., Deiana, G., & Paltrinieri, W. (1994). Structural styles, chronology rates of deformation, and time-space relationships in the Umbria-Marche thrust system (central Apennines, Italy). *Tectonics*, 13(4), 873–881.

- Cancelli, A., Pellegrini, M., Tosatti, G., & others. (1987). Alcuni esempi di deformazioni gravitative profonde di versante nell'Appennino settentrionale. *MEMORIE DELLA SOCIETA' GEOLOGICA ITALIANA*, 39, 447–466.
- Carrara, A., D'elia, B., & Semenza, E. (1985). Classificazione e nomenclatura dei fenomeni franosi. *Geologia Applicata e Idrogeologia*, 20, 223–243.
- Cavinato, G., Cosentino, D., De Rita, D., Funiciello, R., & Parotto, M. (1994). Tectonic-sedimentary evolution of intrapenninic basins and correlation with the volcano-tectonic activity in Central Italy. *Memorie Descrittive della Carta Geologica d'Italia*, 49, 63–76.
- Centamore, E., Dramis, F., Fubelli, G., Molin, P., & Nisio, S. (2003). Elements to correlate marine and continental sedimentary successions in the context of the neotectonic evolution of the central Apennines. *Alpine and Mediterranean Quaternary*, 16(1 bis), 77–87.
- Colesanti, C., & Wasowski, J. (2006). Investigating landslides with space-borne Synthetic Aperture Radar (SAR) interferometry. *Engineering geology*, 88(3–4), 173–199.
- Cruden, D. (1991). A simple definition of a landslide. *Bulletin of Engineering Geology & the Environment*, 43(1).
- Cruden, D. M., & Varnes, D. J. (1996). *Landslide types and processes*. 36–75.
- Deiana, G., Pambianchi, G., & others. (2009). *Note illustrative della Carta Geologica d'Italia alla scala 1: 50.000, foglio 302 TOLENTINO*.

- Dramis, F. (1984). Aspetti geomorfologici e fattori genetici delle deformazioni gravitative profonde. *Bollettino della Società geologica italiana*, 103(4), 681–687.
- Fernández Viejo, G. (1997). *Tectonophysical properties of the lithosphere from seismic refraction studies*. 133–144.
- Ferrero, A. M., Forlani, G., Voyat, I., & others. (2004). Rock slope stability analysis based on photogrammetric surveys. In *Landslides: Evaluation and stabilization* (Vol. 1, pp. 202–208). Lacerda, Ehrlich, Fontoura & Sayao, Taylor & Francis.
- Ferretti, A., Prati, C., & Rocca, F. (2002). Permanent scatterers in SAR interferometry. *IEEE Transactions on geoscience and remote sensing*, 39(1), 8–20.
- Franceschetti, G., & Lanari, R. (2018). *Synthetic aperture radar processing*. CRC press.
- Gabriel, A. K., Goldstein, R. M., & Zebker, H. A. (1989). Mapping small elevation changes over large areas: Differential radar interferometry. *Journal of Geophysical Research: Solid Earth*, 94(B7), 9183–9191.
<https://doi.org/10.1029/jb094ib07p09183>
- García-Cortés, A., Pérez-Estaún, A., & De Vicente, G. (2008). Electrical Resistivity Tomography applications in geotechnical and geological engineering. *Journal of Applied Geophysics*, 71–78.

- Goguel, J. (1978). Scale-dependent rockslide mechanisms, with emphasis on the role of pore fluid vaporization. In *Developments in geotechnical engineering* (Vol. 14, pp. 693–705). Elsevier.
- GPS Overview Part 1: What is GPS and GNSS Positioning?* (s.d.). [Messaggio]. Eos Positioning Systems®, Inc. <https://eos-gnss.com/knowledge-base/gps-overview-1-what-is-gps-and-gnss-positioning>
- Guida, M., & Longo, M. (1988). Estimation of probability tails based on generalized extreme value distributions. *Reliability Engineering & System Safety*, 20(3), 219–242.
- Hu, X., Tang, H., & Li, J. (2008). General digital camera-based experiments for large-scale landslide physical model measurement. In *Landslides and Engineered Slopes. From the Past to the Future, Two Volumes+ CD-ROM* (pp. 271–278). CRC Press.
- Hungerbühler, D., Steinmann, M., Winkler, W., Seward, D., Egüez, A., Peterson, D. E., Helg, U., & Hammer, C. (2002). Neogene stratigraphy and Andean geodynamics of southern Ecuador. *Earth-Science Reviews*, 57(1–2), 75–124.
- Hungr, O. (1981). *Dynamics of rock avalanches and other types of slope movements*.
- Hutchinson, J. (1988). *General report: Morphological and geotechnical parameters of landslides in relation to geology and hydrogeology*.

- Iglesias, R., Mallorqui, J. J., Monells, D., López-Martínez, C., Fabregas, X., Aguasca, A., Gili, J. A., & Corominas, J. (2015). PSI deformation map retrieval by means of temporal sublook coherence on reduced sets of SAR images. *Remote Sensing*, 7(1), 530–563.
- Jeffrey, C. (2010). *An introduction to GNSS: GPS, GLONASS, Galileo and other Global Navigation Satellite Systems* (1st ed). NovAtel.
- Kennerley, J. (1973). Geology of Loja Province, Inst. Geol. Sci. London, Overseas Div. *Unpublished report*, 23.
- Kennerley, J., Bromley, R., & Bromley, R. (1971). *Geology and geomorphology of the Llanganati mountains, Ecuador*. Editorial Minerva.
- Khalili, M. A., Coda, S., Calcaterra, D., & Di Martire, D. (2024). Synergistic use of SAR satellites with deep learning model interpolation for investigating of active landslides in Cuenca, Ecuador. *Geomatics, Natural Hazards and Risk*, 15(1), 2383270.
<https://doi.org/10.1080/19475705.2024.2383270>
- Khalili, M., Bausilio, G., Di Muro, C., Zampelli, S., & Di Martire, D. (2023). Investigating Gravitational Slope Deformations with COSMO-SkyMed-Based Differential Interferometry: A Case Study of San Marco dei Cavoti. *Applied Sciences*, 13(10), 6291.
<https://doi.org/10.3390/app13106291>

- Lanari, R., Mora, O., Manunta, M., Mallorquí, J. J., Berardino, P., & Sansosti, E. (2004). A small-baseline approach for investigating deformations on full-resolution differential SAR interferograms. *IEEE transactions on geoscience and remote sensing*, 42(7), 1377–1386.
- Li, S., He, S., Yue, T., Du, Z., Zhao, N., Zhao, Y., Jiao, Y., Fan, B., Liu, Y., Xu, Z., & Yang, Y. (2023). Mapping bamboo forest and expansion intensity in China by coupling vegetation phenology and C-band SAR with Sentinel-1 and Sentinel-2 images. *International Journal of Applied Earth Observation and Geoinformation*, 121, 103384.
<https://doi.org/10.1016/j.jag.2023.103384>
- Mills, J. P., Buckley, S. J., Mitchell, H., Clarke, P., & Edwards, S. (2005). A geomatics data integration technique for coastal change monitoring. *Earth Surface Processes and Landforms: The Journal of the British Geomorphological Research Group*, 30(6), 651–664.
- Ministerio de Energía y Minas. (2000). *Mapa geológico del Ecuador a escala 1:500.000*.
- Mora, O., Mallorquí, J. J., & Broquetas, A. (2003). Linear and nonlinear terrain deformation maps from a reduced set of interferometric SAR images. *IEEE Transactions on geoscience and remote sensing*, 41(10), 2243–2253.
- MULTILINGUAL, L. G. (s.d.). *UNESCO Working Party for World Landslide Inventory G) 1993*.

- Pagano, L. (2009). The role of rainfall history on the interpretation of flowslide triggering in pyroclastic soils. In *RAINFALL-INDUCED LANDSLIDES* (Vol. 1, pp. 216–223). doppiavoce.
- Polcari, M., Montuori, A., Bignami, C., Moro, M., Stramondo, S., & Tolomei, C. (2017). Using multi-band InSAR data for detecting local deformation phenomena induced by the 2016–2017 Central Italy seismic sequence. *Remote sensing of environment*, 201, 234–242.
- Pratt, W. T., Duque, P., & Ponce, M. (2005). An autochthonous geological model for the eastern Andes of Ecuador. *Tectonophysics*, 399(1–4), 251–278.
- Rizzo, V. (1984). *Alcuni esempi di fenomeni gravitativi profondi nel tentativo di una loro caratterizzazione*.
- Sauer, W. (1958). *El Cerro Hermoso de los Llanganates en el Ecuador*. Editorial Casa de la Cultura Ecuatoriana.
- Sauer, W. & others. (1965). *Geología del Ecuador*.
- Sellers, C., Rodas, R., Carrasco, N. P., De Stefano, R., Di Martire, D., & Ramondini, M. (2020). Ground deformation monitoring of a strategic building affected by slow-moving landslide in Cuenca (Ecuador). *European Workshop on Structural Health Monitoring*, 149–158.
- Sellers, C., Rodas, R., Carrasco, N. P., De Stefano, R., Di Martire, D., & Ramondini, M. (2021). Ground deformation monitoring of a strategic building affected by slow-moving landslide in Cuenca (Ecuador).

European Workshop on Structural Health Monitoring: Special Collection of 2020 Papers-Volume 2, 149–158.

- Shao-tang, L., & Zhi-wu, W. (2008). Choice of surveying methods for landslide monitoring. *Proc. of the 10th International Symposium on Landslides and Engineered Slopes*, 1211–1216.
- Smith, M. J., Chandler, J., & Rose, J. (2009). High spatial resolution data acquisition for the geosciences: Kite aerial photography. *Earth Surface Processes and Landforms*, 34(1), 155–161.
- Soeters, R., & van Westen, C. J. (1996). Slope instability recognition, analysis, and zonation. In *Landslides, investigation and mitigation* (pp. 129–177). National Academy Press.
- Takasu, T. (2009). *RTKLIB: Open Source Program Package for RTK-GPS, FOSS4G 2009 Tokyo, Japan, 2 November 2009*.
- Takasu, T., Kubo, N., & Yasuda, A. (2007). Development, evaluation and application of RTKLIB: A program library for RTK-GPS. *GPS/GNSS symposium, 2007*.
- Terzaghi, K. (1950). *Mechanism of landslides*.
- Tolomei, C., Taramelli, A., Moro, M., Saroli, M., Aringoli, D., & Salvi, S. (2013). Analysis of the deep-seated gravitational slope deformations over Mt. Frascare (Central Italy) with geomorphological assessment and DInSAR approaches. *Geomorphology*, 201, 281–292.

Tschopp, H. (1953). Oil explorations in the Oriente of Ecuador, 1938–1950.

AAPG bulletin, 37(10), 2303–2347.

Vallario, A. (1992). *Frane e territorio: Le frane nella morfogenesi dei versanti e nell'uso del territorio*. Liguori ed.

Varnes, D. J. (1958a). Landslide types and processes. *Landslides and engineering practice*, 24, 20–47.

Varnes, D. J. (1958b). Landslide types and processes. *Landslides and engineering practice*, 24, 20–47.

Varnes, D. J. (1978). Slope movement types and processes. *Special report*, 176(11), e33.

Wieczorek, G. F. (1996). Landslides: Investigation and mitigation. Chapter 4- Landslide triggering mechanisms. *Transportation Research Board Special Report*, 247.

Wolf, T. (1892). *Geografía y geología del Ecuador: Publicada por orden del Supremo Gobierno de la República*. FA Brockhaus.

(S.d.). In *Treccani* (p. <https://www.treccani.it/vocabolario/monitoraggio>).

