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Investigating the kinematics of the unstable slope of Barberà de la Conca (Catalonia, Spain) and the effects on the exposed facilities by GBSAR and multi-source conventional monitoring

Abstract The paper presents a multi-source approach tailored for the analysis of ground movements affecting the village of Barberà de la Conca (Tarragona, Catalonia, Spain), where cracks on the ground and damage of different severity to structures and infrastructure was recorded. For this purpose, monitoring of ground displacements performed by topographic survey, geotechnical monitoring and remote sensing techniques (ground-based synthetic aperture radar, GBSAR) are combined with multi-temporal damage surveys and monitoring of cracks (crackmeters) to get an insight into the kinematics of the urban slope. The obtained results highlight the correspondence between the monitoring data and the effects on the exposed facilities induced by ground displacements, which seem to occur predominantly in the horizontal plane with diverging directions (northward and southward) from the main ground fracture crossing the centre of the village. The case study stands as a further contribution to fostering this kind of integrated approaches that via cross-validations can improve data reliability as well as enrich datasets for slope instability recognition and analysis, which are crucial to plan risk mitigation works.

Keywords Ground movements · Monitoring · GBSAR · Building damage · Geotechnical investigations

Introduction

Ground mass movements threaten private and public properties and human life with significant socio-economic loss. The diagnosis of predisposing factors and causes of unstable ground as well as understanding the spatial/temporal evolution and the interaction with the exposed elements (i.e. urban areas) are key steps for hazard assessment and risk management, and for the definition, design and implementation of mitigation strategies (Fell et al. 2008; Corominas et al. 2014; Mansour et al. 2011; Ferlisi et al. 2019). In particular, the geometric and kinematic characterization of mass movements is a challenging goal that is essential for the later understanding of the mechanism and, then, to be able to analyse the causes and the conditioning factors. This is commonly achieved by geological-geomorphological methods and monitoring of ground displacements performed by topographic, geotechnical and, more recently, remote sensing techniques such as differential interferometric synthetic aperture radar (DInSAR) (Antronico et al. 2013; Calò et al. 2014; Crosetto et al. 2016; Del Soldato et al. 2018; Di Maio et al. 2018; Frattini et al. 2018; Gullà et al. 2017; Noviello et al. 2020; Peduto et al. 2017, 2018; Solari et al. 2020; Tofani et al. 2013; Wasowski and Pisano 2019). However, the use of ground-based and

conventional monitoring systems (e.g. total stations, Global Navigation Satellite System (GNSS) receivers, extensometers, tiltmeters and inclinometers), though providing accurate spatial and temporal information on the surface/subsurface displacements, can turn out to be difficult and unaffordable when the investigation has to cover large urban areas for long periods. Despite the presence of buildings and infrastructures can hamper the reconnaissance of the typical signs of instability (Gullà et al. 2017), conversely under these conditions, the detailed analysis of effects on the exposed elements (e.g. cracks on building façades and/or road pavement, retaining walls, etc.) can turn out to be useful for the comprehensive diagnosis of slope mechanism (Cascini et al. 2013; De Novellis et al. 2016; Peduto et al. 2016a, 2017, 2019; Nicodemo et al. 2017; Nappo et al. 2019; Del Soldato et al. 2019). In particular, photo comparison of damage to buildings taken at different times can allow for the identification of mass movement boundaries and their activity assessment (Ferlisi et al. 2015; Borrelli et al. 2018; Nicodemo et al. 2018, 2020; Peduto et al. 2016b, 2018, 2019).

Currently, satellite-based synthetic aperture radar (SAR) systems can acquire regularly data over repeated passes (Hanssen 2001; Colesanti and Wasowski 2006; Crosetto et al. 2016). They are able to achieve centimetric to millimetric accuracy and to assess slope stability conditions in urban areas, e.g. see Crosetto et al. (2011) and Noviello et al. (2020). A complementary data source is given by ground-based SAR (GBSAR) (Noferini et al. 2005; Monserrat et al. 2014). A GBSAR system allows the monitoring of deformation with a precision that ranges from sub-millimetres to a few millimetres; it can measure at distances up to some kilometres, independently of the atmospheric conditions and typically can cover an area of 1–2 km², with a dense measuring coverage (Carlà et al. 2019; Dick et al. 2015; Ferrigno et al. 2017; Iglesias et al. 2013; Iannini and Guarnieri 2011; Leva et al. 2003, 2005; Luzi et al. 2004, 2006).

The paper presents a multi-source approach tailored for the analysis of ground movements affecting the hill where the village of Barberà de la Conca (Tarragona, Catalonia, Spain) is placed and damage of different severity to structures and infrastructure was recorded (Janeras et al. 2017). With the aim of characterizing the kinematics of the area, a procedure based on the merge of different conventional (topographic and geotechnical) and remote sensing displacement monitoring techniques (GBSAR) together with the results of multi-temporal building damage surveys was implemented. Although the area is densely built-up, the results allowed the definition of the prevailing movement direction and the analysis of damage distribution as well as its severity level.

Materials

Geological settings

The municipality of Barberà de la Conca (Fig. 1) is located in the province of Tarragona, in Catalonia (Spain), very close to the town of Montblanc. It extends over an area of 26.6 km² and it hosted about 473 inhabitants in 2019 (IDESCAT 2020).

The village, dominated by the Church of Santa Maria (Fig. 1c), with a height of 475 m a.s.l., is located in a large pit excavated by the Francolí and the Anguera rivers on the southern bank of the Central Depression, separated from the Camp of Tarragona by the Prelitoral Mountain Range (ICGC 2011, 2012, 2015a,b,c), forming a rather smooth topography territory composed by hills and ravines. On the south side, there is a steep slope covering a 30-m topographic height difference, whereas a gentle slope is present on the north side. From the geological point of view (Fig. 1b), the

municipality rests on a Paleogene stratum composed by ancient deposits of fluvial (PElx) and fluvio-alluvial (PEcgg) sediments. The upper part of the hill where the town is placed is constituted by a harder layer with conglomerate in a slight tabular relief diving to the northwest. The rest of the ground is mainly formed by red siltstone with gypsum veins.

Geotechnical investigations

In order to investigate the characteristics of the geomaterials composing the subsoil of the study area, geotechnical investigations were carried out (ICGC 2013). This geotechnical characterisation consisted of continuous drilling surveys in three main areas (Fig. 2): test field 1 “Valentí Almirall street”; test field 2 “Bruc and St. Victorià Streets”; and test field 3 “Church of Santa Maria”. Ten boreholes were carried out along with representative soil sampling of the crossed layers with a total amount of 101 linear meters of perforation (ICGC 2013). The

Fig. 1 Barberà de la Conca study area. **a** Map of the urban area with digital elevation model (DEM). **b** Geo-lithological map (scale: 1:50,000; source: ICGC, 2016, www.icgc.cat). **c** View of the study area

Fig. 2 Locations of borehole surveys with derived geotechnical logs (modified from ICGC, 2015a) and map of five (I-1, I-2, I-4, I-5 and I-6) installed inclinometers with azimuth and cumulative horizontal displacements recorded in the observation period spanning from November 2011 to February 2012

different recorded geomaterials (Fig. 2) were then grouped into four main geotechnical units: quartzite and calcareous conglomerate (PEcunit); argillite and clays (PEa and PEca units); fine grained sandstone (Peg unit); high/medium (PEaa unit); and low consistence altered clay (PEab unit).

This investigation allowed identifying an upper altered level group of materials without presence of gypsum and a lower unaltered level with abundant presence of gypsum veins.

Problem description, damage survey and conventional monitoring network

Since November 2010, on appointment delivered by the City Council of Barberà de la Conca, the Cartographic and Geologic Institute of Catalunya (ICGC), has been studying the instabilities affecting the municipality. To this aim, a technical survey was carried out on the area of interest (Fig. 3a) to detect the presence of cracks on the ground and to record eventually the damage affecting the buildings and/or the roads. As preliminary result, the recorded ground crack was mapped (Fig. 3b). In particular, the crack path starts from the Carrer Valentí Almirall street (approximate altitude: 448 m a.s.l.), ascending in north-east orientation to the Church of Santa Maria (approximate altitude: 475 m a.s.l.) and

then, stretching downhill north slope in a parallel direction to Raval del Castell street (approximate altitude: 462 m a.s.l.), with a mapped length of approximately 175 m (ICGC 2012).

A second survey (carried out by ICGC on 24th February, 2011) over the affected area (Fig. 3a) was commissioned by the City Council of Barberà de la Conca due to the widening of previously detected cracks and the development of new cracks affecting also the buildings present in the urban centre. From this date on, both visual surveys of the urban area and manual/automatic monitoring—which was progressively implemented and extended until now—were started to investigate the real causes of the ground movements. The visual inspections carried out over the years by ICGC technicians and data provided by the installed building monitoring network allowed retrieving in 2016 a comprehensive building damage map (Fig. 3b) in which the recorded severity levels were classified adopting the Earthquake Engineering Research Institute (EERI) ranking (see also Table 1 in the “Methods” section) based on the interpretation of the crack patterns (in terms of width and extension of cracks) exhibited by the building façades.

The implemented monitoring network (starting from the early 2011) over the study area (ICGC 2018) includes (Figs. 2 and 3b) five inclinometers; topographic benchmarks (7 alignments with 23 geo-points and 25 prisms); five GPS bases; and building crack sensors

Fig. 3 Barberà de la Conca study area. **a** Area of interest. **b** Map of the ground crack path detected during the in situ survey with the recorded building damage severity levels classified (in 2016) according to the EERI ranking and monitoring networks including building crack sensors (showed in c), topographic levelling and GPS

(4 digital vibrating wire crackmeters “VWC” and 50 tell-tale crack monitors).

In particular, in order to detect the presence of slip surfaces related to mechanisms of a possible landslide in the south slope of the hill, a geotechnical monitoring of the study area was performed including the installation of inclinometers (Fig. 2). In the period spanning from November 2011 to February 2012, the cumulative horizontal displacements recorded by the five (I-1, I-2, I-4, I-5 and I-6) inclinometers that were installed in the area (ICGC 2012) did not exhibit a homogeneous direction of the azimuthal movements as well as no clear sign of the presence of a slip surface was detected within the investigated depths deeper than the base of the hill slope.

Additionally, the installed topographic network (Fig. 3b) is composed by 2 subnets: the former includes 7 levelling alignments with several control points composed by geo-points embedded on the building walls and reflective mini-prisms located at a height of about 3 m (ICGC 2013); the latter include 5 GPS

bases that provide absolute movements of points located on the building roofs.

Crackmeters (Fig. 3c) were installed on the architectural elements in order to monitor the width of building cracks induced by the ground movements. The network is composed by 4 VWCs with automatic and continuous measurements of crack width with a precision of 0.015 mm and repeatability of ± 0.3 mm. The rest of the devices composing the monitoring network are tell-tale crack monitors installed on buildings to follow the evolution of crack patterns by comparing successive acquisition on a monthly basis (ICGC 2018).

GBSAR monitoring

In addition to the conventional monitoring network, GBSAR monitoring (Fig. 4) was implemented in the period spanning from 2011 to 2017. In fact, after the first urgent survey and monitoring activities previously described, the superficial ground movements

Fig. 4 GBSAR monitoring over the Barberà de la Conca study area. **a** Location of the two GBSAR acquisition points (POS1 and POS2). **b** Photo of the GBSAR system during an acquisition campaign; spatial distribution of cumulative LOS displacement measurements recorded from **c** POS1 in the period 2011–2017 and **d** POS2 in the period 2015–2017

affecting the whole urban slope were investigated by using GBSAR monitoring to get an overview of kinematics.

The GBSAR data acquisition was based on the so-called discontinuous approach, which was repeated twice, observing the village from two opposite points of view: a first position located south of the municipality (POS1 in Fig. 4a) and a second position located in the north part of the village (POS2 in Fig. 4a). The used GBSAR system is the IBIS-L owned by CTTC and manufactured by IDS (Ingegneria dei Sistemi SpA). The system consists of three main modules: the radar sensor (Fig. 4b), the rail on which the radar moves on during an acquisition and the power together with the computer that configures and controls the measurement (Monserrat et al. 2014). In this study, the position of the GBSAR was selected with the aim of having a good visibility of the village.

As for POS1, 13 measurement campaigns were carried out from 14th November 2011 to 13th December 2017. In the first campaign, 8 control points were materialized in the GBSAR installation area to recover its position in the following campaigns. It should be noted that the recovery of the position with an accuracy of a few centimetres is enough. For each acquisition campaign, several acquisitions were carried out and a single image with a lower noise level was generated.

Seven measurement campaigns were carried out from POS2 (in the period from 4th June 2015 to 14th December 2017).

In addition, a laser scanner (TLS) campaign was carried out to generate a high-quality digital terrain model and thereby improve the georeferencing of GBSAR points. Figure 4c and d show the recorded cumulative line-of-sight (LOS) displacement for POS1 in the period 2011–2017 (with an azimuth of 340°) and POS2 in the period 2015–2017 (with an azimuth equal to 180°). In both cases, positive (blue) values indicate displacements towards the viewing sensor, whereas the red points indicate displacements away from the sensor.

Methods

Figure 5 illustrates the used procedure, which was based on monitoring and building damage data. Monitoring data included

GBSAR measurements (datasets coming from two different points of view) and topographic measurements (levelling and GPS), whereas the building damage information was derived from multi-temporal building damage surveys (dated 2016 and 2018) and crack monitoring sensors.

The two processed GBSAR datasets were preliminary cross-compared to check their inherent consistency; then, they were validated with the available topographic measurements in order to derive the *Displacement Map* of the study area (Fig. 5). For this purpose, the 3D topographic measurements were projected along the LOS of the GBSAR following the steps described in the Appendix.

As for the building damage data, the results of multi-temporal damage surveys and the measurements retrieved by the crack sensor network were used to generate a quantitatively based *Damage Map* (Fig. 5). Information on the crack patterns exhibited by the building façades and collected during consecutive in-situ surveys was preliminarily homogenized in order to analyse the building damage evolution in the time; then, it was linked to the measurements performed by the crack sensor network. To this aim, the damage severity levels assigned to each surveyed building in 2016 considering the EERI categories (Fig. 2b) were associated with the damage levels of Burland et al.'s (1977) classification system, which relies on the ease of damage repair and crack width (Table 1) and it is widely used in geotechnical engineering to investigate the damage suffered by building walls as a consequence of ground movements. This ranking, used for the successive damage survey carried out in 2018, considers six categories of damage (from Do = negligible to D5 = very severe) that can be grouped in three main classes. These latter can affect (i) the aesthetics (categories Do, D1 and D2) with crack widths ranging from less than 0.1 mm up to 5 mm, (ii) the functionality (categories 3 and 4) with crack widths up to 15 mm and (iii) the stability (category 5) with crack widths exceeding 25 mm.

Finally, the displacement and damage maps were jointly analysed to get an insight into the kinematics of the study area.

Fig. 5 Flowchart of the followed procedure

Table 1 EERI ranking vs. Burland et al. (1977) classification system

Damage severity level Burland et al. 1977	EERI	Crack width [mm] (Burland et al. 1977)	Description (EERI)
D0 No damage	Null	0	Without damage
D1/D2 Very slight/slight	Slight	0–5	Non-structural damage with a repair cost less than 5% of market value
D3 Moderate	Moderate	5–25	Sizable non-structural damage and slight structural damage with a repair cost less than 25% of market value
D4 Severe	Severe	25–50	Considerable structural damage and very high non-structural damage with a repair cost less than 50% of market value
D5 Very severe	Total	50–100	When is cheaper demolish than repair
	Collapse	> 100	When the entire structure has collapsed

Results

Cross-comparison (topographic vs. GBSAR data) and displacement map

The dataset provided by the GBSAR technique (Fig. 4) was acquired during the measurement campaigns (Table 2) carried out from two different positions (POS1 and POS2). It consists of 1080 benchmarks recorded from POS1—covering a monitoring period of about 6 years (14th November 2011 to 13th December 2017)—and 400 benchmarks acquired from POS2 during about 3 years (4th June 2015 to 14th December 2017). An overall agreement between the movements towards/away from each POS can be noticed in Fig. 4c and d.

Then, according to the followed procedure (Fig. 5), a cross-comparison of the two GBSAR datasets with topographic measurements was carried out with respect to the available observation periods for POS1 and POS2. For this purpose, the available 3D measurements provided by the topographic monitoring network were projected along the GBSAR LOS (Fig. 6c) according to the procedure shown in the Appendix. Figure 6a and b shows a good

matching between different monitoring systems. In addition to this, a quantitative comparison (an example is shown in Fig. 6d) was carried out over a total of 201 GBSAR measurements points selected among those falling within a 10-m buffer around each topographic benchmark, in order to take into account the geolocalization errors between the two monitoring systems. The result provided an average value of velocity difference between the two monitoring systems in the observation periods along the same direction (GBSAR LOS) equal to 3.47 mm/year, with a standard deviation of 2.95 mm/year.

Damage analysis: in-situ surveys and monitoring data

The second step of the analysis focused on the interpretation and classification of the building damage resulting from both multi-temporal surveys (dated 2016 and 2018) and measurements by crackmeters. In order to investigate the building damage evolution, in addition to the information on the damage suffered by buildings in 2016 (Fig. 3b), a new expeditious building damage survey was carried out in 2018. Moreover, the crack patterns derived by the visual inspections of the buildings' façades carried out in 2016 were re-analysed and classified according to Burland et al. (1977) as shown in Table 1. The result of the multi-temporal damage surveys to 254 buildings is shown in Fig. 7a and b. Table 3 summarizes the total amount of buildings belonging to each damage severity class per each dataset.

The maps of Fig. 7a and b show that most of the damaged buildings are distributed along the main crack path detected on the ground in 2016. However, notwithstanding the generalized increase of the building damage recorded between the two surveys, the 2018 damage map (Fig. 7b) reports only 17 buildings exhibiting a very severe damage level (D5) due to repair interventions carried out on some buildings in the period 2016–2018 (Fig. 7c). Furthermore, the recorded building damage severity levels were combined with the data acquired by the crackmeters considering only the cracks width measured in the time between the two surveys (2016–2018); width values were grouped in Fig. 7b according to the ranges proposed by Burland's classification (Table 1). An overall agreement can be appreciated between the values recorded by the crackmeters and the damage severity levels suffered by the buildings. Exception is made for two buildings positioned in the west

Table 2 GBSAR measurement campaign from POS1 and POS2

Measurement campaign	Acquisition date POS1	POS2
1	14_11_2011	X
2	19_12_2011	X
3	08_05_2012	X
4	20_03_2013	X
5	04_06_2015	04_06_2015
6	15_12_2015	15_12_2015
7	02_08_2016	02_08_2016
8	13_12_2016	13_12_2016
9	05_04_2017	05_04_2017
10	18_07_2017	X
11	10_10_2017	09_10_2017
12	14_12_2017	14_12_2017

Fig. 6 Cross-comparison of GBSAR displacement data acquired from **a** POS1 and **b** POS2 and topographic benchmarks projected along the GBSAR line of sight (LOS) following the scheme shown in (c). **d** An example of cross-check between GBSAR and topographic measurements

Technical Note

Table 3 Number of buildings per damage level for both 2016 and 2018 building damage surveys

Damage level	2016	2018
D0	117	73
D1/D2	91	68
D3	12	67
D4	16	29
D5	18	17

side of the study area (framed in the black circles in Fig. 7a and b and shown in Fig. 7c). These buildings exhibited D5 damage level in 2016 and D4 and D1/D2 in 2018 (probably due to slight repair interventions including normal decoration of the building walls carried out in 2018, see Fig. 7c); conversely, crack width values correspond to D5 damage level because they cumulated up to the date of repair (Table 1).

Furthermore, it is worth stressing that the 2018 survey revealed that the original main crack path recorded in 2016 has further extended in the eastward direction (see the magenta dashed line in Fig. 7b), as also testified by the surrounding buildings showing in the 2018 survey an increased damage severity level compared to the one recorded in 2016.

The derived *Displacement* (Fig. 6) and *Damage* (Fig. 7) maps were finally combined in a single *Displacement-Damage* map (Fig. 8) in order to have an overview of the kinematics of the urban area taking into account all the considered data for the period from 4th June 2015 to 14th December 2017 when GBSAR data for both positions are available. The derived *Displacement-Damage* map (Fig. 8)—in which the blue points are moving southward, green points are stable and yellow/orange/red points are moving northward—shows diverging displacements in correspondence of the main ground crack path. This latter crosses the Church of Santa Maria that is one of the most affected building with a damage severity level equal to D5. Many other buildings record high displacements but during the 2018 survey showed low

Fig. 8 Overview of the kinematics (displacements) and building damage severity levels affecting the study area

damage severity levels. This aspect could be related to different causes, such as (i) the buildings are not so close to the main crack where differential displacements prevail, (ii) the building façade (visible from the street) was repaired before the 2018 survey and (iii) some displacement measuring points were not located on the façades (e.g. on electricity line piles, antennas, chimneys).

Discussion and conclusion

The kinematic characterization of unstable slopes affecting urban areas is a challenging goal that can be pursued via geological and/or geotechnical methods and monitoring of ground displacements achieved by the integration of conventional techniques and, more recently, ground-based synthetic aperture radar (GBSAR) data. In this regard, a useful additional contribution can be provided by damage inventories recorded on buildings located on urban slopes, although the building (foundation and superstructure) response may result from a combination of different factors such as deep ground driving factors, surface effects of the ground (due to geotechnical and slope asymmetry) as well the structural response of the building itself.

Although the integration of all the above-mentioned methods should be planned a priori to be more effective, datasets resulting from the independent use of these different methods are commonly available (see for instance Gullà et al. 2017), thus making crucial the need for their integration.

The results obtained in such a complex context as the village of Barberà de la Conca highlighted the correspondence between kinematical analysis and the outcomes of the monitoring campaigns including geotechnical (inclinometers), topographical (levelling and GPS), remote sensing (GBSAR), structural (crackmeters) monitoring and damage surveys. From the obtained results, ground displacements appear as mainly horizontal moving towards opposite directions (northward and southward) from the main ground fracture crossing the centre of the village. Along this fracture, the buildings with the highest damage level are concentrated, according to the extension movement, as testified also by the highest values of crack widths recorded by structural monitoring. These building cracks seem to have increased with the passing of time resulting in an increase of the damage severity level to many buildings in the area, in agreement with the progressive opening of the main ground crack at constant velocity and the slight increase of its extension to the east end.

The deep ground displacement monitoring with inclinometers, although very limited in time, seems to show the absence of a clear slip surface within the investigated depth. Moreover, a second-order vertical displacement between both borders of the main fracture crossing the centre of the village was detected by ICGC as shown in its monthly report dated December 2017 (ICGC 2018). This combination of movements with both horizontal and vertical components along the main crack seem to match the concentration of most severe damage to buildings in this portion of the village.

Current limits to the study concern the cause of the ground mass movement that is not yet well known. The most plausible hypothesis puts its origin at deep ground level, lower than 100 m depth, as a response of mineralogical mechanisms that transform anhydrite (CaSO_4) to gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$). This behaviour has been described in a similar geological formation

during the construction of high-speed railway tunnel near Barberà de la Conca (Alonso et al. 2005) and also has been described in Staufen (Germany), where the constructions of seven geothermal borehole heat exchanger led to enormous structural damage to buildings due a swelling deep anhydrite formation (Sass and Burbaum 2010).

The currently obtained results on the kinematics of the slope of Barberà de la Conca have addressed further and more detailed investigations on the causes of the phenomenon by means of deeper boreholes and a mineralogical analysis in order to establish the origin of the sulphate minerals and their dynamics related with hydrogeology. These further deepening will be necessary to plan and design appropriate control works for risk mitigation.

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Appendix

Hereafter, the projection of 3D topographic displacement data along the GBSAR line of sight (LOS) is briefly described. The reader can refer to Fig. 6c.

Considering east (E), north (N) and height (H) of GBSAR position (POS) coordinates:

$$POS_{(E,N,H)GBSAR} = \{E_{POS}, N_{POS}, H_{POS}\} \quad (1)$$

and east (E), north (N) and height (H) of the i -th topographic point (P) coordinates:

$$P_{(E,N,H)topographic} = \{E_P, N_P, H_P\} \quad (2)$$

obtained as difference, in each direction, between the final and initial position of the considered topographic point [$E_P = E_{P,f} - E_{P,i}$; $N_P = N_{P,f} - N_{P,i}$; $H_P = H_{P,f} - H_{P,i}$], the projection of displacement vector of the topographic point $\bar{S}_P = \{S_E, S_N, S_H\}$ along the GBSAR LOS direction $\bar{S}_{P_LOS}$, can be evaluated according to Eq. 3

$$\bar{S}_{P_LOS} = \bar{S}_P \times \overline{LOS}_{vers} = (S_E \times E_{vers}) + (S_N \times N_{vers}) + (S_H \times H_{vers}) \quad (3)$$

where the east (E), north (N) and high (H) component of Line of Sight versor $\overline{LOS}_{vers} = \{E_{vers}, N_{vers}, H_{vers}\}$ are derived using the Line of Sight versor equation (Eq.4):

$$\overline{LOS}_{vers} = \frac{\overline{LOS}}{\|\overline{LOS}\|} = \frac{\{E_{LOS}, N_{LOS}, H_{LOS}\}}{\sqrt{E_{LOS}^2 + N_{LOS}^2 + H_{LOS}^2}} \quad (4)$$

in which the Line of Sight vector components $\overline{LOS} = \{E_{LOS}, N_{LOS}, H_{LOS}\}$ are evaluated using the Line of Sight equation (Eq.5):

$$\overline{LOS} = (E_P - E_{POS})\hat{i} + (N_P - N_{POS})\hat{j} + (H_P - H_{POS})\hat{k} \quad (5)$$

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