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Differential single-frequency GPS monitoring of the La Valette landslide (French Alps)

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Abstract

Recently, Global Positioning System (GPS) surveying techniques have been increasingly employed to monitor landslide movement. Here we present an application of GPS to monitor the La Valette landslide, located in the Ubaye Valley in the southern French Alps. This complex landslide is composed by an upper rotational part, a central part with generally translational movement and a lower part, which occasionally transforms into mud flows during intense rainfall events. Displacement rates average a few centimeters per month, with velocity peaks of some centimeters per day during periods of strong activity. GPS data presented in this study were acquired with two single-frequency GPS receivers Magellan connected to multipath-resistant antennas. The data were processed with the Magellan software MSTAR. Nine points have been set in the studied area, seven of them in the moving area, one in a stable area near the landslide and one on the facing slope, which is used as reference point. For each observation, one GPS receiver is placed on the reference point for the whole day and the second one is placed on each monitored point for 1-h sessions. The distance between the base and monitored point ranges from 480 to 1660 m. Eight survey campaigns were made between October 2000 and October 2002, to follow the evolution of the surface displacements. The maximum cumulative 3-D displacement observed in the area was about 21 m during the period in the center part of the landslide, corresponding to an average rate of movement of about 3 cm/day. The accuracy achieved during the GPS measurements has been evaluated to be about 2.4 cm in E–W direction, about 11 cm in N–S direction and about 7.4 cm in elevation in the worst case. The GPS results have been compared with traditional surveying techniques (EDM) carried out on the same site by RTM Service (Restauration des Terrains en Montagne). The velocities obtained by the two methods are similar. The advantage of the GPS technique is the collection of data for the three spatial coordinates (x, y, z) of each point, which allow to calculate the 3-D displacement vector. These measurements have been combined with SAR interferometric data in order to analyse the temporal evolution of the different landslide sectors.

Keywords: Differential single-frequency GPS; Landslide; Monitoring; French Alps

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1. Introduction

In the last decade, the Global Positioning System (GPS) techniques have been widely applied to monitor the superficial movements of unstable areas, both as a complement to conventional surveying methods and as a valid alternative to them. The application of the GPS system to landslide monitoring is also increasing. Examples can be found on the large number of recent publications on this topic (see for example, Gili et al., 2000; Duranthon, 2000; Moss, 2000; Malet et al., 2002; Rutigliano et al., 2002; Coe et al., 2003). The results of these works confirm the GPS survey technique as a helpful tool in landslide monitoring application, in case of surface movements ranging from a few cm per month to some cm per day. The validation of GPS data carried out with EDM (Electronic Distance Measurement), extensometric, topographic and inclinometric measurements shows a practical precision of the method ranging between mm, in case of continuous monitoring (Malet et al., 2002; Rutigliano et al., 2002), to a few cm, in case of discontinuous rapid static or static positioning (Moss, 2000; Coe et al., 2003).

The major advantages in using GPS surveying techniques compared to optical methods are: (i) GPS surveying allows to acquire a large number of high-resolution observables at relative high speed and low cost; (ii) GPS can monitor large areas (up to 20 km distance) without drastic reduction of the precision of the measurements; (iii) GPS do not need direct visibility between base and monitoring point; (iv) GPS works in any weather condition. Despite these positive features, encouraging widespread use of this monitoring technique, the accurate determination of the location of points often requires the use of dual-frequency GPS receivers. GPS satellites broadcast continuously on two frequencies carrying position and time information. Single-frequency GPS receivers register only one wavelength, which can be affected by atmospheric effects during its travel. Dual-frequency receivers work with the two wavelengths which are affected differentially by atmosphere. Post-processing of dual-frequency data can at least partially correct the errors caused by the signal interaction with the atmosphere. This type of instrumentation, which is able to perform position determinations with an absolute precision less than 1 cm, is normally rather expensive (about three times more expensive than the single-frequency equipment) and the post-processing of the collected data requires specialized software and an experienced operator.

The purpose of this work is to show the capabilities of relatively low cost single-frequency GPS equipment, used in differential mode, to follow surface displacements. In differential mode, some local errors, such as clock errors, incorrect orbit determination, ionospheric and troposphere effects, induced in the same way on both receivers can be reduced or canceled in the post-processing phase. The application site is La Valette landslide, located in the southern French Alps, near the Barcelonnette village. The results of eight measure campaigns are presented, carried out between October 2000 and October 2002. A comparison between GPS and EDM measurements and between GPS and differential SAR interferometric results is shown, with the aim to validate the GPS displacement data and to enhance the surface evolution study already carried out on the La Valette landslide.

2. The La Valette landslide

The “La Valette” landslide is located in the southern French Alps, north of the Mercantour massif, near the Barcelonnette village, on the right side of the Ubaye valley (Fig. 1).

The geological sequence of the landslide slope consists of, from the base to the top, the Callovo-Oxfordian “Terres Noires” formation, which is mainly a closely stratified black marl forming the central and lower parts of the slope, and the Helminthoid Flysch of the Ubaye-Embrunais nappes, dated Upper Cretaceous–Upper Eocene, forming the upper part of the slope and composed by black schists, locally with layers or blocks of limestone and sandstone (Kerckhove, 1969). The geological contact between the two formations is a thrust fault, which puts in contact two formations with very different hydrogeological properties. The contact between the impermeable “Terres Noires” and the highly fracturated and highly permeable flysch formations favours water circulation in correspondence of the thrust fault, where a large number of springs have been mapped (Dupont and Taluy, 2000). On the lower part of the slope, up to

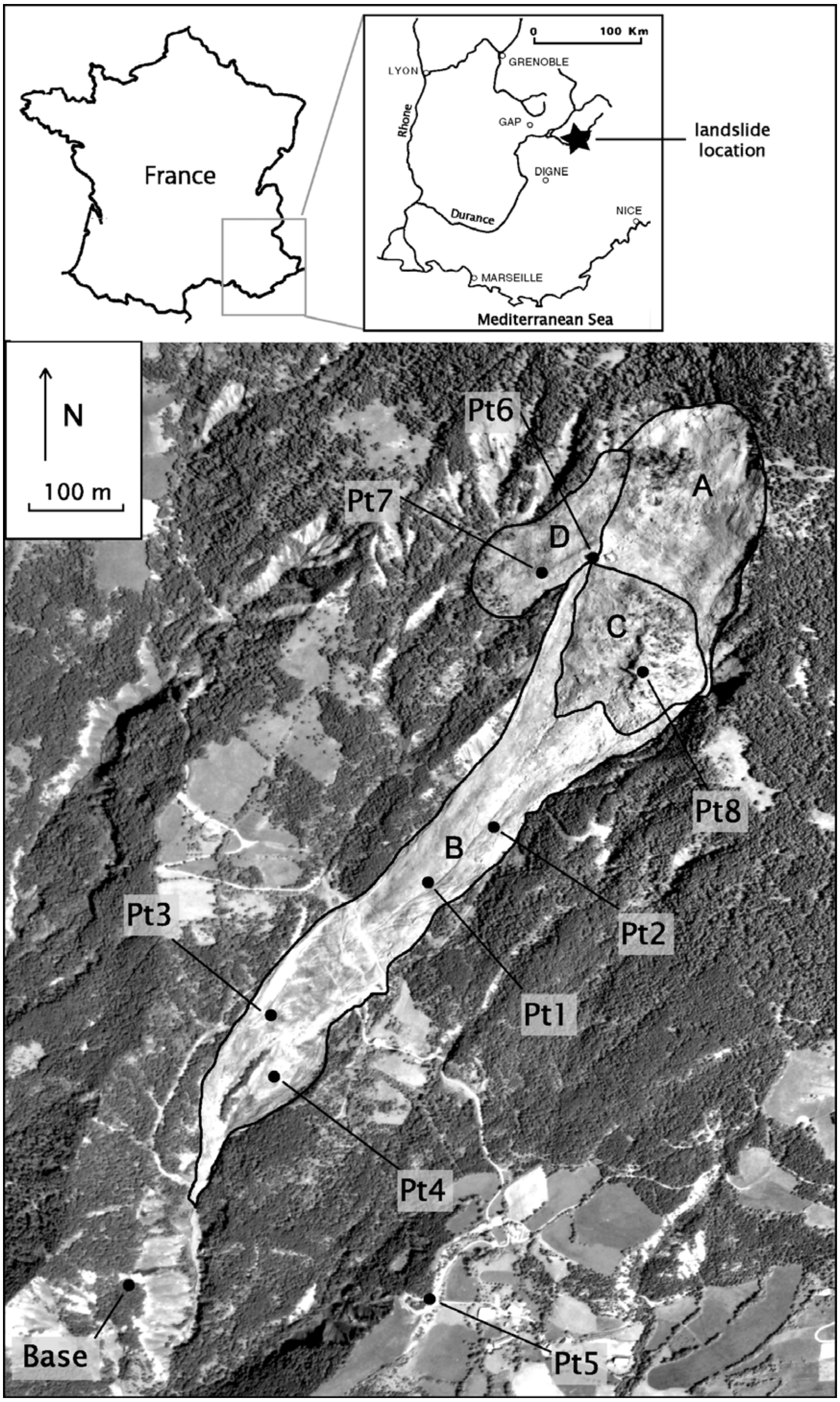

Fig. 1. Aerial photograph taken in 1996 of the La Valette landslide area, located in the southern French Alps. The black outline shows four distinct zones in the landslide, identified by geomorphological studies and ground surveys. The zones are characterised by a different surface morphology and evolution (sectors A, B, C, D; see text for explanations). The location of GPS base and monitoring points is shown (e.g. Pt1).

1500 m elevation, the sequence is covered with Quaternary deposits consisting of Würm glaciation morainic deposits of the Ubaye valley glacier.

From a geomorphological point of view, four zones of the landslide can be distinguished (Potherat, 2000; Squarzoni et al., 2003): (Fig. 1) an upper part (sector A), formed by a nearly vertical scarp in the black schists reshaped by the landslide evolution; a lower part (sector B), characterized by the principal earth-flow mainly constituted of black marls and moraines; a highly fractured limestone cliff about 200 m wide (sector C) located at the base of the main scarp, that generates abundant rock fall and produces a steep debris accumulation of rock masses of as much as some tens of cubic meters; a second, smaller earth-flow (sector D), developed from the upper western side of the main landslide body. Currently the instability involves an area of about 0.5 km^2, extending between 1900 m and 1300 m elevation, with a length of about 2000 m and a width at the top of the landslide of 450 m. The depth of the sliding surface in the middle part of the landslide has been estimated to be about 25 m by means of seismic profiles (Evin, 1992).

The landslide began moving in 1982 in the upper part, in correspondence of the thrust fault (Colas and Locat, 1993) and enlarged on the rest of the slope, involving the “Terres Noires” and the morainic deposits. This created a complex landslide structure, with an upper part affected essentially by rotational mechanism, a central part with a generally translational movement (Potherat, 2000; Squarzoni et al., 2003) and a lower part that occasionally transforms into mud flow in coincidence with intense rainfall events.

Surface displacement data are already available from EDM measurements, carried out by the “Restauration des Terrains en Montagne” Service (RTM), and from differential SAR interferometric studies (Vietmeier et al., 1999; Squarzoni et al., 2003). The EDM measurements provide a history of the landslide surface evolution since 1988, showing two velocity peaks of a few tens of cm per day in periods of intense activity (spring–summer 1989 and autumn–winter 1991–1992) and an average velocity of about 5 cm/day. A general deceleration begins in 1996, with mean annual velocity values decreasing to about 0.8 cm/day in the central part.

The four geomorphological sectors described above have also been kinematically characterized using differential SAR interferometric analysis of the surface displacement, carried out on some radar data acquired between 1991 and 1999 (Squarzoni et al., 2003). The results of this study show that the upper part of sector B and sector A have the fastest movement, with maximum velocity values of around 2 cm per day during 1996, decreasing to about 0.4 in 1999. The same decreasing trend revealed since 1996 by EDM measurements is shown.

3. GPS equipment and method of data acquisition

The GPS system and surveying principles have been described by other authors (see for example Leick, 1995; Hofmann-Wellenhof et al., 2001).

The GPS data presented in this study were acquired with two single-frequency hand-held GPS receivers, each equipped with an external antenna limiting multi-path reflection problems. Nine measurement points have been set in the study area, seven of them in the landslide body, one on the facing slope, used as reference point, and an additional one in a stable area southwest of the landslide (Fig. 1).

Because of the geomorphological and kinematical heterogeneities of the landslide area, the location of the monitoring points has been chosen to observe the evolution of zones with different surface velocities. For this purpose, four GPS points have been placed in the principal earth-flow (sector B—points 1, 2, 3, 4 in Fig. 1), the first two located upstream and the second two downstream of the country road at about 1500 m elevation; another point has been set in the secondary smaller earth-flow (sector D—point 7); one other on a rocky outcrop in correspondence to the limestone cliff on the top of the debris accumulation (Rocher Blanc, sector C—point 8); a last one on a rock block of about 30 m^3 located approximately at the limit between the principal and the secondary earth-flow (point 6).

GPS antennas used for the measuring surveys have been mounted on a tube 1.3 m high, installed in a concrete base inserted a few tens of centimeters in the ground (points 1, 2, 3, 4, 5, 7) or cemented on the rock mass (points 6 and 8) (Fig. 2). Before each measurement, the distance of the phase center of the antenna from the base of the point’s monument, as well as the

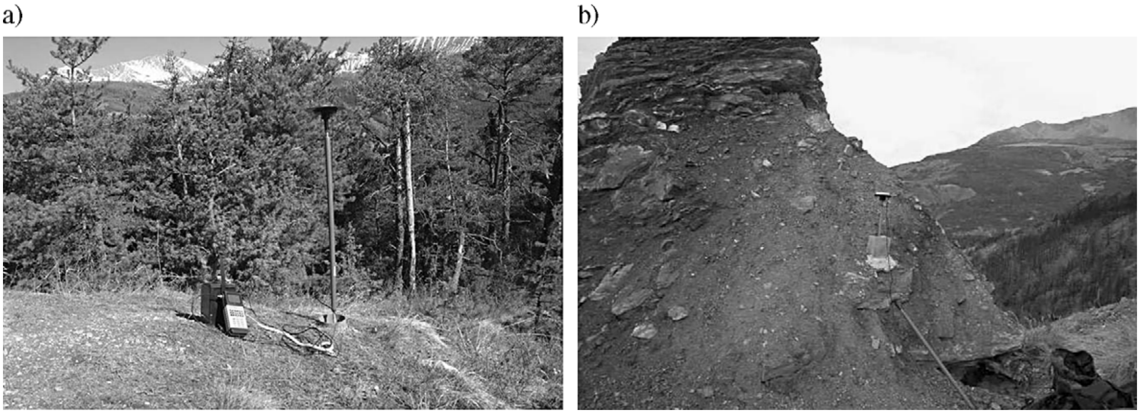

Fig. 2. Two GPS antenna installations. a) Reference point: the concrete base is inserted a few tens of centimeters in the terrain; b) Pt6: the base is cemented on the rock mass surface.

angle between the tube and the vertical, were systematically measured and taken into account in the post-processing step.

Eight survey campaigns were made between October 2000 and October 2002, to follow the evolution of the surface displacements (Table 1). The first four points have been monitored for all the campaigns, the points 6, 7 and 8 have been measured six times since May 2001, because they were installed later, and point 5 has been measured only four times, because its position is out of the moving area.

For each field campaign, the static acquisition method has been used (Hofmann-Wellenhof et al., 2001), with one GPS receiver placed on the reference point for the entire day and the second one on each monitoring point for about 1 h. The GPS data collected in each campaign were processed with the Magellan's MSTAR post-processing software. This software uses a method of double differences and gives correct positions with accuracy of 15 mm±3 ppm. Nevertheless, considering the short baseline (480–1660 m) between reference and remote point, no ionospheric and tropospheric corrections are needed (Malet et al., 2002).

Table 1
Dates of GPS campaigns with the elapsed time (in days) between each campaign

Dates of GPS campaigns	Time elapsed (days)
October 30–November 01, 2000	–
April 29–May 03, 2001	181
June 06–08, 2001	38
August 05–10, 2001	60
October 13–14, 2001	69
April 17, 2002	186
May 13–16, 2002	26
October 07–08, 2002	147

4. GPS results and comparison with EDM measurements and SAR interferometric analysis

4.1. Landslide movements from GPS data analysis

The results of the GPS measurements are shown for each point as horizontal displacement (Fig. 3), as total elevation variation versus time (Fig. 4) and as total 3-D displacement versus time (Fig. 5). The maximum displacement observed in the landslide in the two years is about 21 m. Fig. 3 shows that the general direction of movement in the *x–y* plane is nearly parallel to the average topographic surface; some variations are visible, linked to local topographic variations and local heterogeneities in the landslide motion. The comparison between the horizontal and the vertical displacement components for each point shows that the movement develops mainly on the horizontal plane (Fig. 6).

Kinematic heterogeneities in the landslide body are recognized by the GPS data analysis, identifying zones affected by different superficial activity. The central part of the landslide (upper part of sector B),

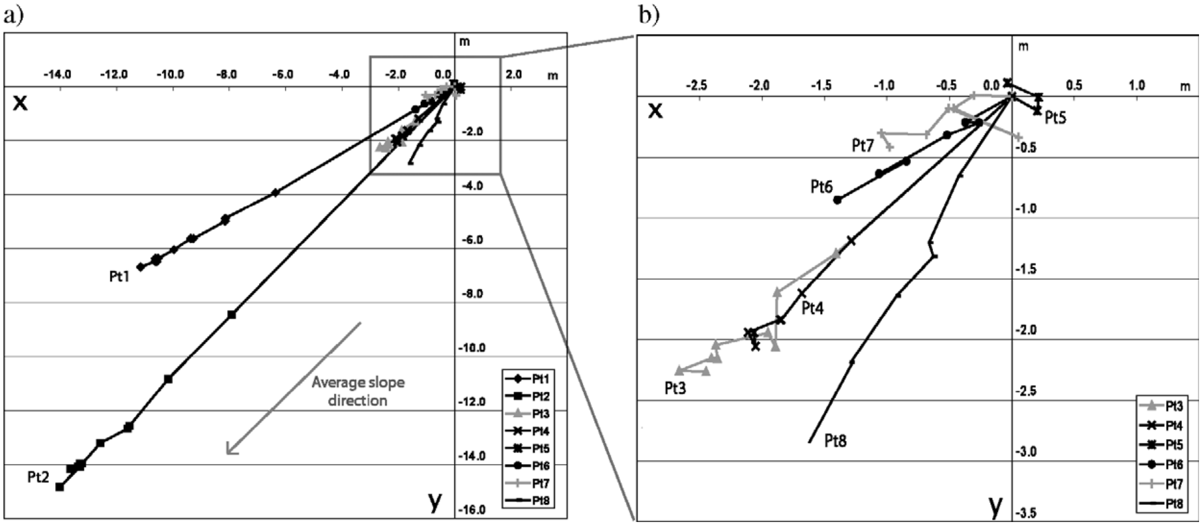

Fig. 3. a) Cumulative horizontal displacement measured for each point in the whole monitoring period, taking the first measurement as reference. b) Detail of the cumulative horizontal displacement for the points moving less than 4 m.

including Pt1 and Pt2, reveals higher displacement compared with the other sectors of the landslide, confirming the results of the differential SAR interferometric study (Squarzoni et al., 2003). The total displacement of Pt2, the maximum observed along the two years, is about 21 m, with a vertical component of about −3.6 m (Fig. 4).

Pt3 and Pt4, located in the lower part of the sector B, and Pt8, installed on a rock mass in the sector C, show similar amount of total displacement of about 3 m. However their evolution is quite different; looking at the two components of the movement (Fig. 7), the vertical component for Pt8 (1.50 cm) is greater than for the other two points (0.74 and 0.48 cm respec-

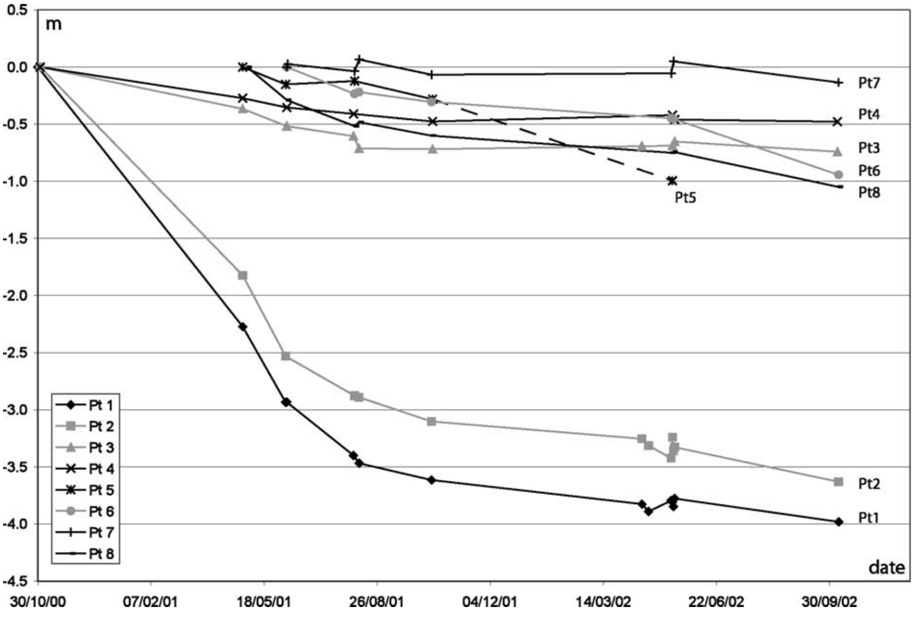

Fig. 4. Elevation variations vs. time measured at each point from the first measurement.

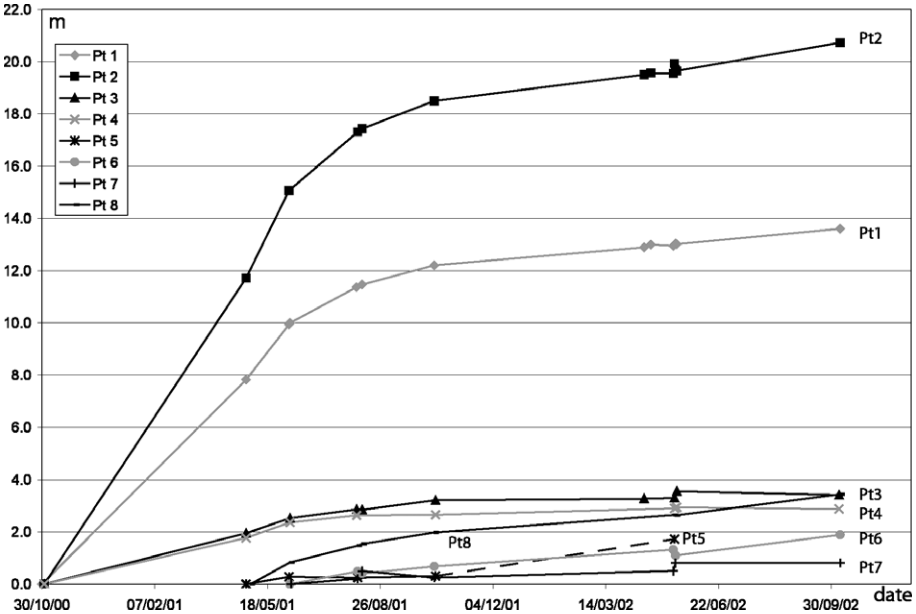

Fig. 5. Total 3-D displacement vs. time of each monitoring point from the first measurement.

tively for Pt3 and Pt4). This can be explained by observing the relative position of the three points in the landslide area: Pt3 and Pt4 are located in the lower zone of the earth-flow, having a gentle local slope and moving quite parallel to it; the movement of Pt8, installed at the top of a steep scarp, reflects the slow collapse of the scarp itself (Fig. 7).

The displacement of Pt7, moving about 1 m in the whole period, illustrates the lower activity of the smaller earth-flow (sector D), developing from the western flank of the main body, with respect to the major earth-flow. Its displacement in both horizontal and vertical components is rather irregular, suggesting an independent evolution of the sector D with respect to the main landslide body. This confirms the observations already done by Squarzoni et al. (2003), where the results from the SAR interferometric analysis show a non-stationary rate of deformation of the sector D between 1991 and 1999.

The position of Pt6 was chosen at the limit between the two sectors B and D, with the purpose to better understand the spatial evolution of the smaller earth-

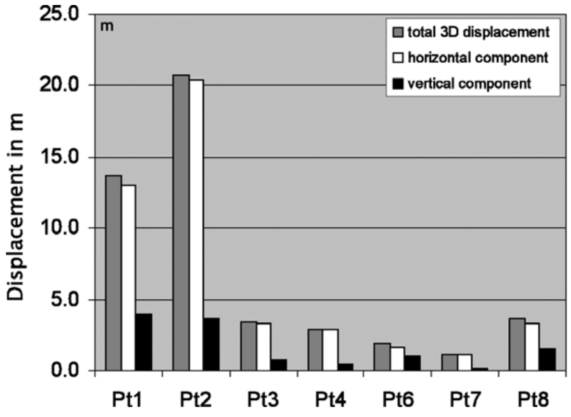

Fig. 6. Contribution of the horizontal and vertical components of the motion in the total 3-D displacement for each GPS point located in the landslide.

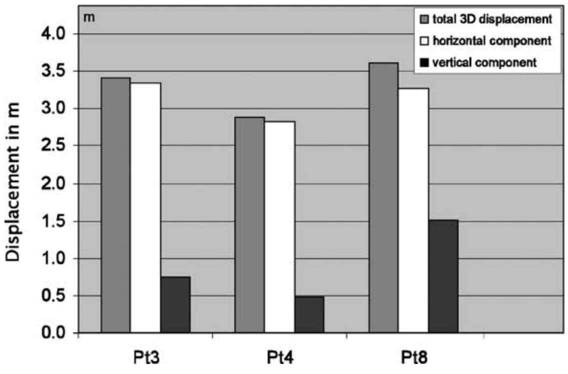

Fig. 7. Contribution of the horizontal and vertical components of displacement for the GPS points Pt3, Pt4 and Pt8.

flow. An analysis of the displacement trend in the horizontal plane shows that Pt6 moves nearly in the same direction of Pt7, with a direction of about 240° from North, representing the general direction of the topographic slope in the second earth-flow. Therefore, Pt6 can be considered as belonging to sector D, allowing better definition of the internal limits of the landslide.

The comparison between the displacement of the GPS points installed in the two earth-flows (sectors B and D) with time shows a similar evolution of the two sectors: the upper part of each of the two earth-flows is affected by a greater movement than the lower part.

From a temporal point of view, a comparison between the displacement values of the GPS points in the periods October 2000–October 2001 and October 2001–October 2002 shows that all the monitoring points located in the moving area accelerated during the first year compared to the mean annual value of displacement reported by RTM (0.9 cm per day in 2000), with a successive deceleration beginning in October 2001 (Fig. 8). This temporal variability is shown by the important decrease in the slope of the total 3-D displacement curves in correspondence with October 2001 (Fig. 5). This acceleration is probably linked with the meteorological conditions of fall 2000 and spring 2001, characterized by rainfall of about three times more than the mean average rainfall computed for the period 1954–2001. The only exceptions are Pt6 and Pt7, which show displacement amounts of +17 cm and +6 cm respectively in the second year compared to displacements in the first year of monitoring. This can be explained with the fact that these two points, together with Pt8, were installed later and then measured only beginning in June 2001 rather than from October 2000, the period of major activity. Moreover, a careful analysis of the elevation changes of Pt1 and Pt2 shows an anomalous variation between April and May 2002, where displacement values are generally low. This is probably due to the generally lower accuracy of GPS methods in the vertical coordinate determination compared with the planimetric one (Hofmann-Wellenhof et al., 2001).

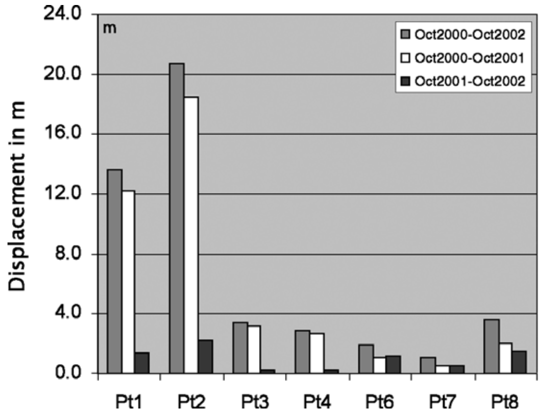

Fig. 8. Contribution of each year (October 2000–October 2001 and October 2001–October 2002) on the displacement of each monitoring point compared to the total displacement (October 2000–October 2002). Pt6, Pt7 and Pt8 were measured beginning June 2001.

4.2. Precision estimation of GPS measurements

Estimating the precision of GPS measurements in the coordinate determination can be performed in two ways. The first is the analysis of the apparent movement shown by Pt5, installed in a stable location. This point has been surveyed four times, but a precise solution was never accomplished because of insufficient number of observables. Interference caused by the close proximity of some electric cables is a possible cause. The obtained values are plotted in Fig. 9. The error bars correspond to two times the value of the standard deviation for each measurement and for each type of data (3-D, horizontal, vertical), including a theoretical 95.4% confidence interval. The maximum difference in the coordinate values is about 25 cm in E–W direction, 23 cm in N–S direction and 32 cm in elevation. The relative error bars partially overlap for the total 3-D displacement (Fig. 9c); for the elevation variation they overlap except for the first measurement, whose distance from the second measurement is only a few millimeters (Fig. 9b); in the horizontal plane the error bars in E–W direction overlap, while in the N–S direction the bars have a distance of several centimeters (Fig. 9a).

The second way to estimate the precision of GPS measurements is the analysis of the displacement data measuring the same monitoring point on consecutive days. With this purpose, the position of Pt1 was measured four times, at May 13, 14, 15 and 16, 2002. The expected displacement, estimated using the average displacement observed between October

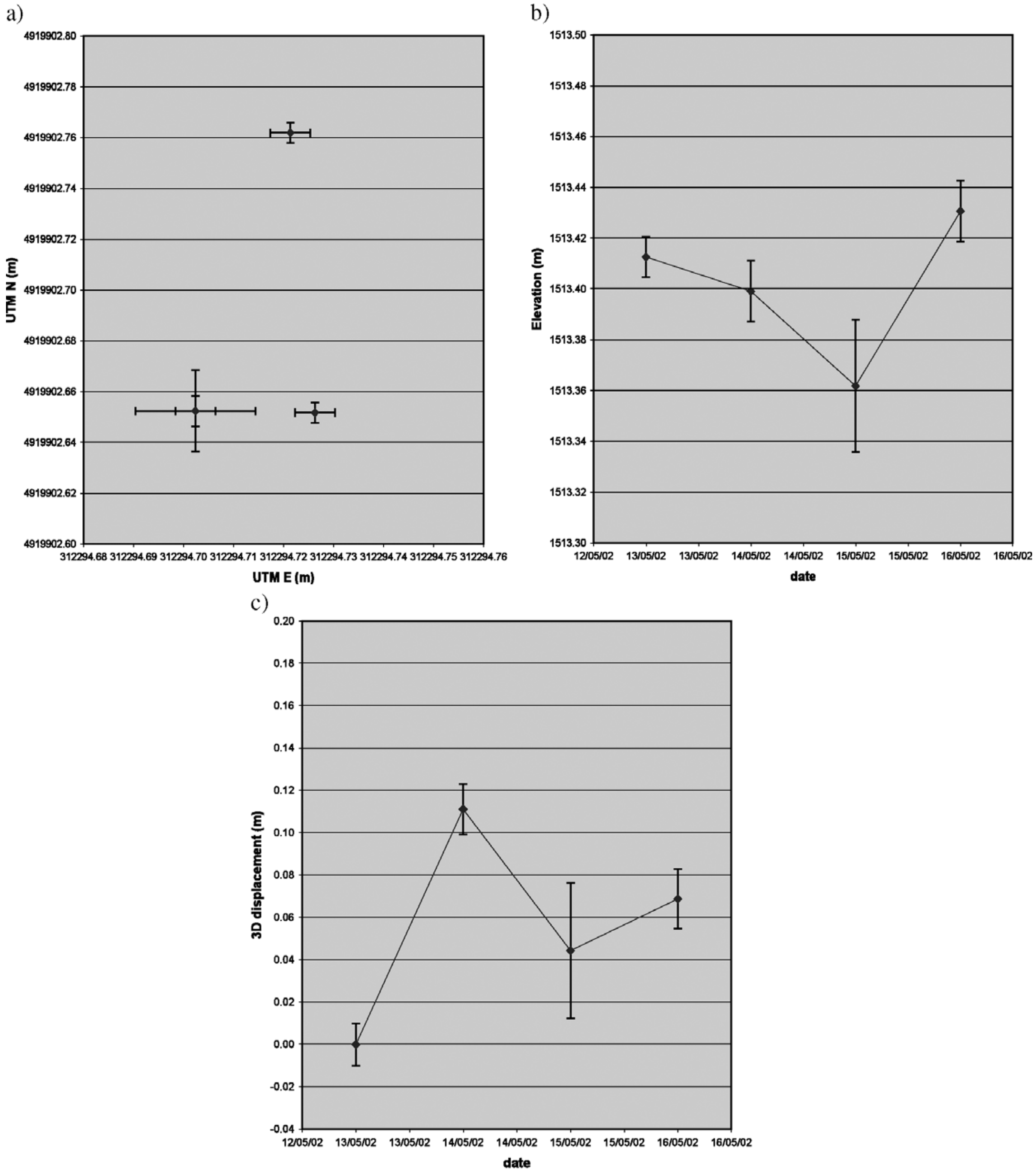

Fig. 9. Apparent movement of Pt5, located outside the landslide area. The error bars correspond to two times the standard deviation for each measurement, including theoretical 95.4% confidence interval. a) Horizontal displacement. b) Elevation variation. c) Total 3-D displacement.

2001 and October 2002, is 0.4 cm/day. The GPS values, together with the respective error bars computed as before, are shown in Fig. 10. The error bars are not well overlapping, with values ranging from 0.4 cm to 1.6 cm in the horizontal plane (Fig. 10a), from 0.8 cm to 2.6 cm in elevation (Fig. 10b) and from 1 cm to 3.2 cm in the 3-D determination (Fig. 10c). As expected, the error in the vertical component is greater than the planimetric error (Gili et al., 2000). The measured values of 3-D position span about 11 cm, the values in the horizontal plane span about 2.4 cm in E–W direction and about 11 cm in N–S direction, while the elevation values span about 7.5 cm. The 3-D position interval is mainly governed by the N–S and the vertical components. On the contrary, the N–S component shows an anomalous trend in comparison with the E–W component: the N coordinate for the first day is about 11 cm beyond that from the other days. It is quite unlikely that a real displacement between two successive days is so large with respect to the following days. Moreover, the value of PDOP (Position Dilution of the Precision, see Hofmann-Wellenhof et al., 2001 for details) related to this measurement was very low (1.73). Thus we attribute this anomaly to a local problem of multipath linked to this measurement or to an instrument malfunction during this measurement.

Assuming that no movement occurred at Pt1, these observations lead to estimate in about 11 cm the operative accuracy of the GPS equipment in 3-D. The components of the accuracy can be estimated, in the worst case, to be about 2.4 cm in E–W direction, about 11 cm in N–S direction and about 7.4 cm in elevation. The coordinate calculation could be realistically improved using different GPS post-processing software that is able to integrate the use of the precise orbits calculated from a fixed ground network instead of the broadcast ephemeredes collected directly from the GPS satellites.

4.3. Comparison between GPS and EDM measurements

The GPS results have been compared with the electronic distance meter (EDM) measurements acquired at the study area by RTM Service. The position of the GPS reference point in the slope facing the landslide has been intentionally chosen next to the EDM control point. In the same way, Pt1 and Pt2 in the landslide body have been installed next to two EDM points (respectively P19 and P18). The distance between EDM and GPS points is about 2 m for the reference point and about 1 m for the other two points. Therefore, this configuration allows for comparison of these two networks the respective baselines between control and monitoring points (Fig. 11). The trend of displacement is exactly the same, with displacement towards the reference point of 12.5 m for Pt1 and more than 20 m for Pt2 during the period when the data overlap. The gap between the absolute displacement values is due to the actual distance between GPS and EDM points (they are not coincident). Moreover, from a temporal standpoint, the analysis of the EDM data highlights an acceleration of the landslide motion between October 2000 and July 2001, with a following deceleration beginning in October 2001. As was stated in the previous subsection, GPS data alone were able to identify this acceleration and deceleration, confirming the kinematic variation. The good agreement between the two types of displacement data confirms the accuracy of the single frequency GPS equipment used in this study.

4.4. Integration with differential SAR interferometric results

Differential SAR interferometry is a powerful tool for surface motion analysis and provides a spatial representation of the movement field (Massonnet and Feigl, 1998). A SAR interferometric study has been performed in the study area, to assess the temporal and spatial heterogeneities in the landslide motion (Squarzoni et al., 2003). The available SAR data correspond to a set of differential interferograms, each showing the displacement during a single day (TANDEM acquisition series). The GPS measurements presented above and the available TANDEM SAR interferometric data are unfortunately not overlapping in time: the GPS measure campaigns began in October 2000, while the SAR images were acquired between 1991 and 1999, when the landslide activity was slower than in 2000. Nevertheless, the two types of motion data can be integrated to qualitatively analyse the temporal evolution of the different landslide sectors.

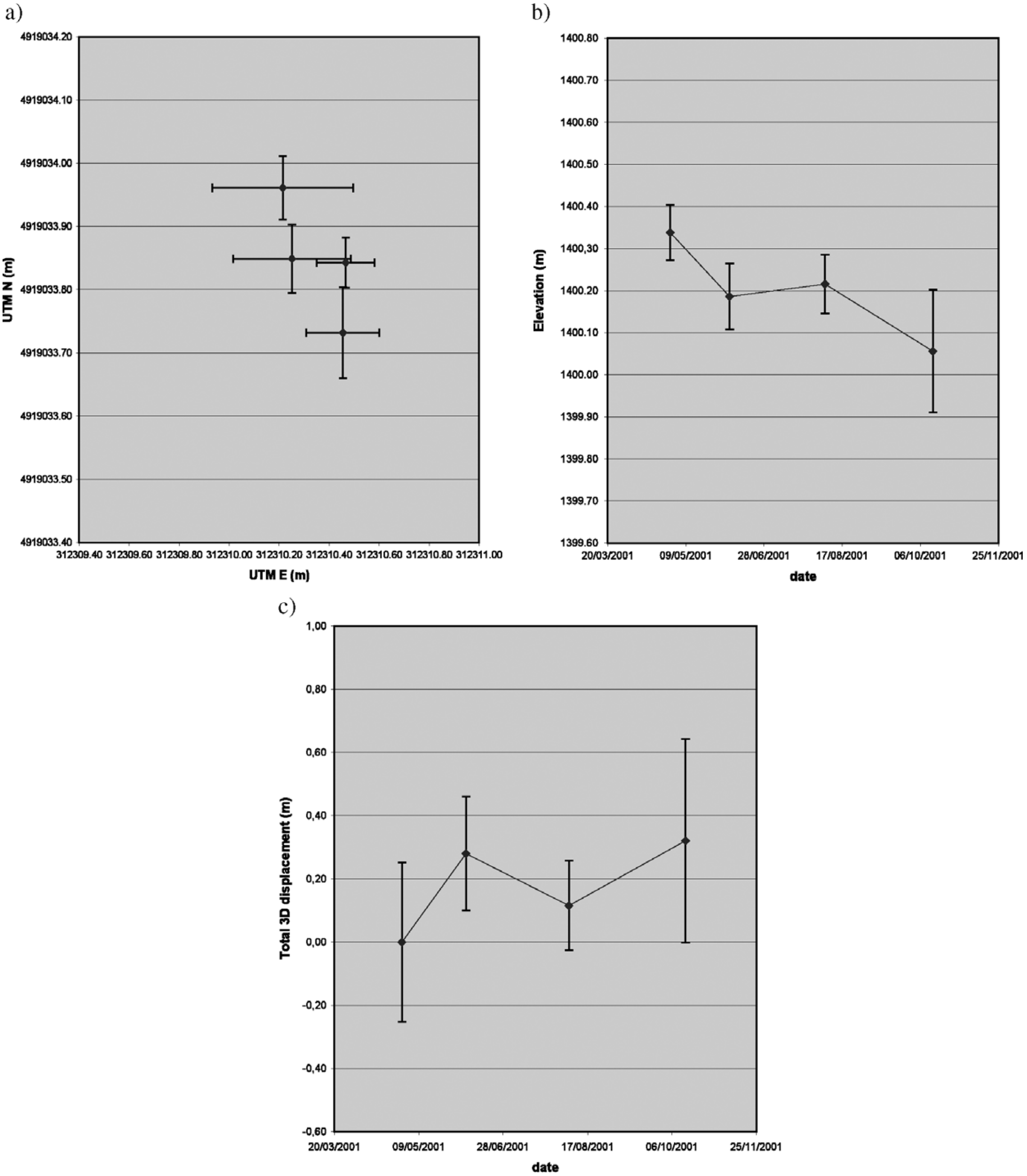

Fig. 10. Analysis of displacement data of Pt1 in four successive days. The error bars are defined as in Fig. 9. a) Horizontal displacement. b) Elevation variation. c) Total 3-D displacement.

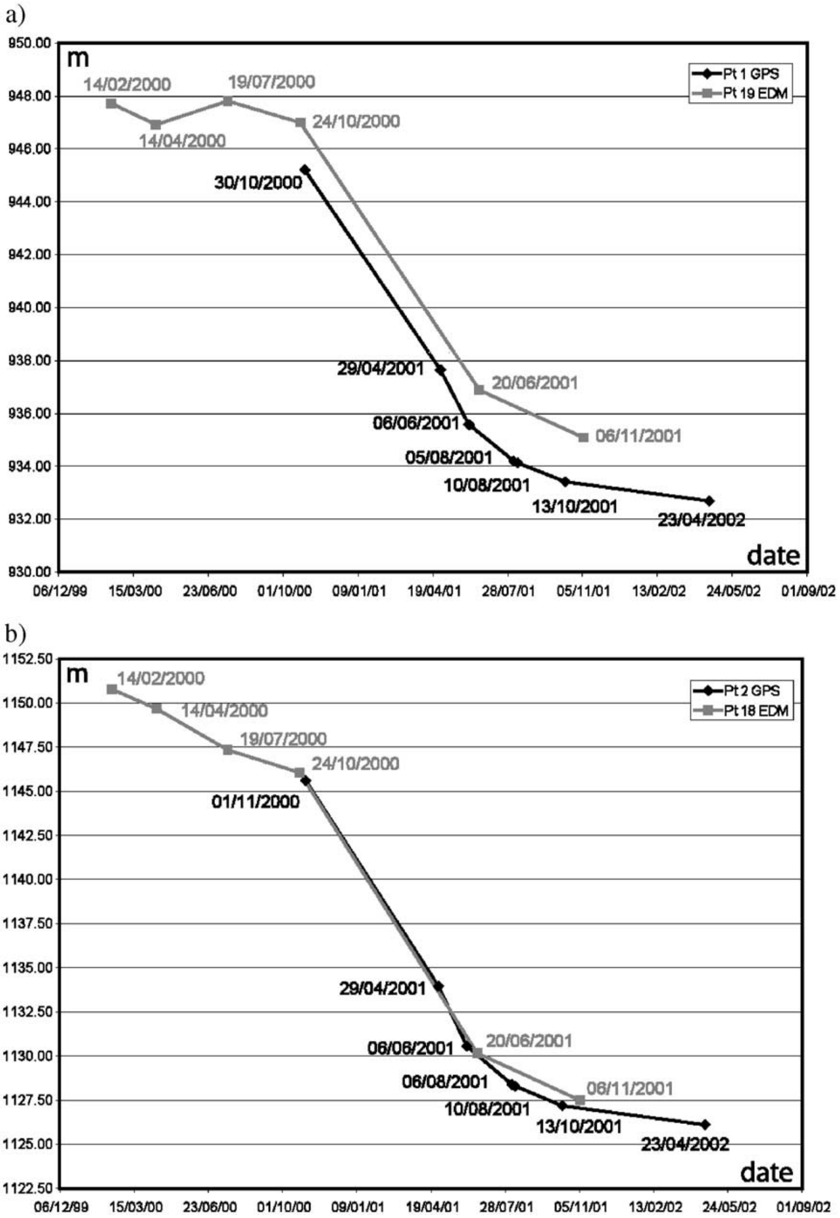

Fig. 11. Comparison between GPS and EDM measurements in terms of baseline variation between base and monitoring point vs. time. a) Baseline variation for the points GPS-Pt1 and EDM-Pt19, installed a few tens of centimeters apart. b) Baseline variation for the points GPS-Pt2 and EDM-Pt18, installed around 1 m apart.

For this purpose, only three TANDEM differential interferograms have been considered, acquired in October 1995, April 1996 and May 1997. The displacement values at each GPS point have been estimated from the analysis of each interferometric SAR product and projected to the average landslide slope. The final values have been plotted in a graph (Fig. 12). The average GPS velocity (in cm/day) between October 2000 and October 2002 for each monitoring point has been calculated and shown in the same graph as the interferometric values. In the same way, the average GPS velocities measured from

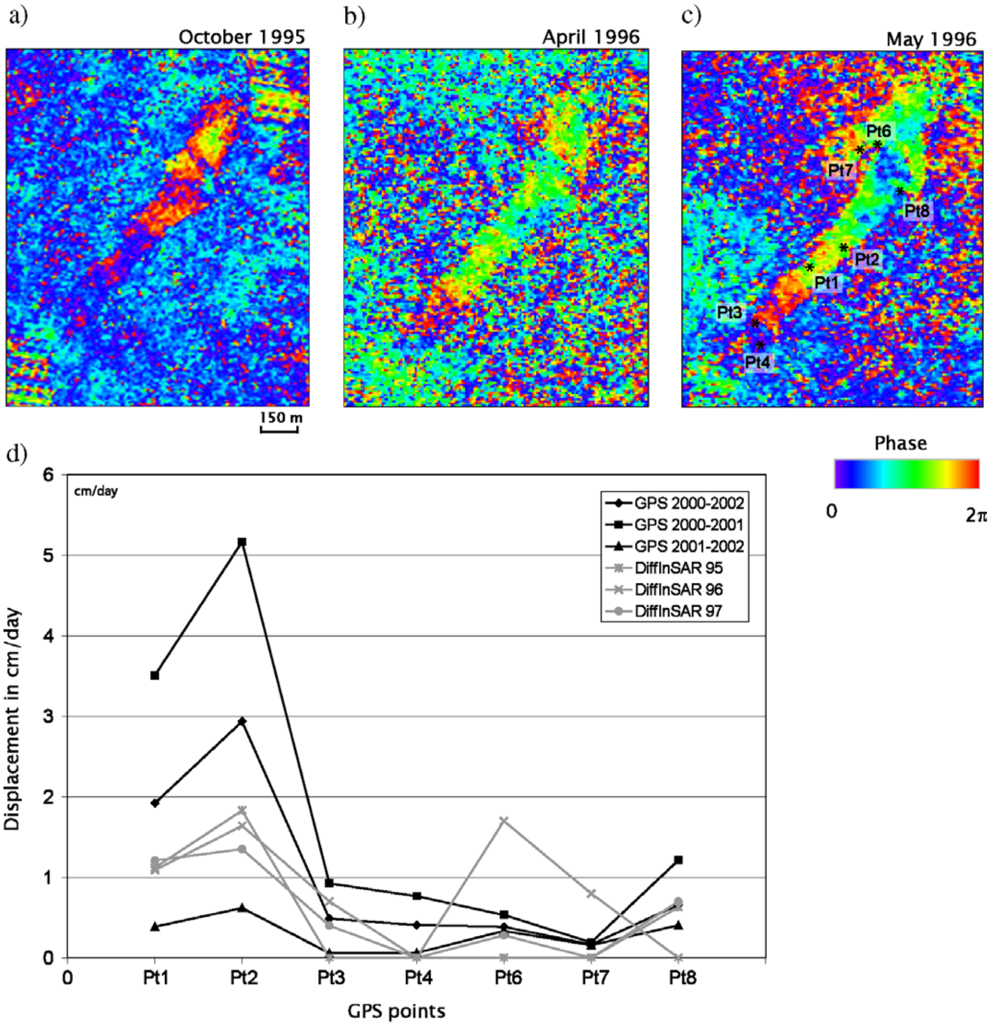

Fig. 12. Comparison between differential SAR data and GPS measurements. a), b) and c) represent the three differential interferograms considered in this study, dated respectively October 1995, April 1996 and May 1999. The black stars in figure c) represent the location of the GPS points. d) Average GPS velocity values (in cm/day) of each GPS point for the whole monitoring period, for each monitoring year and velocity values estimated from the SAR analysis for the same points.

October 2000 to October 2001 and from October 2001 to October 2002 are shown.

The results show that the relative velocities measured with the two methods are of the same order of magnitude. Pt1 and Pt2 are always the fastest, with a greater activity for Pt2. An exception is apparent for Pt6, which presents an anomalous velocity in the April 1996 interferogram, which we interpret as the non-uniform motion of this part of the landslide (sector D), which moved independently of the main landslide body and maybe associated with different groundwater conditions (Squarzoni et al., 2003). The slow activity of the lower parts of the two earth-flows (lower part of sector B and lower part of sector D represented respectively by Pt3, Pt4 and Pt7) relative to that of the upper part of the same sector is again shown and has the lowest velocity values. The higher activity in the first year of GPS measurements in comparison with the SAR results is emphasized, confirming the rapid motion during the spring 2001 with respect to the previous years.

5. Discussion and conclusion

The use of GPS surveying techniques in monitoring of the La Valette landslide demonstrates the capabilities of low cost single-frequency GPS equipment for this kind of study and is validated by the comparison with EDM measurements. GPS results confirm the existence of different landslide zones affected by varying degrees of activity previously demonstrated by SAR interferometric studies. Moreover, GPS data analysis allows the precise mapping of the boundaries between the distinct zones within the landslide area.

The apparent motion of the stable point prevented us from determining the precision of the instrumentation used because of the signal interference at this location. Nevertheless, the repeatability of the measures, tested on one point for four successive days, gives some estimate to the minimum displacement required between two successive acquisitions; for this site surveyed with this instrumentation, it is about 2.4 cm in longitude, about 11 cm in latitude and about 7.4 cm in elevation in the worst case.

The installation of another fixed point, located far from any kind of electrical cable or any reflecting surface that may cause signal perturbations or multipath, could provide a better estimate of the practical precision of our GPS instrumentation. Moreover, it should be noted that the orientation of landslide slope, together with the steepness in its upper part, helps to obscure part of the sky. For this reason, the number of simultaneously observable satellites with an elevation mask of 15° was generally between 4 and 6. This suggests that the accuracy is probably underestimated with respect to a GPS campaign carried out in areas with no obstruction of the sky.

As expected, the accuracy obtained in this work with single-frequencies GPS receivers is lower than that reported in other published work using dual-frequencies receivers. For example, in Gili et al. (2000) values of 30 and 40 mm for the planimetric error and 46 and 62 mm for the elevation error are given respectively, in terms of 99% of confidence interval for fast static (FS) and real-time kinematic (RTK) field methods. This suggests that the practical frequency of measurements on the same landslide will be approximately halved with the single-frequency equipment used in this work compared to a dual-frequency equipment as that used by Gili et al. (2000).

The different characteristics of spatial resolution of the GPS technique with respect to the satellite SAR interferometric data (pixel size of 10 m in the case of SAR data, point values in the case of GPS data) allow to consider the two methods as complementary: the SAR technique can be used to identify and preliminarily map the area in motion and follow the displacement with the temporal resolution imposed by the availability of the satellite radar images. GPS survey of monumented points, located from field observations and SAR results, allows for better mapping of the slide limits and monitoring the motion with the suitable temporal resolution. In addition, GPS measurements allow for the calculation of the 3-D component of displacement, with a greater accuracy in the horizontal plane with respect to the vertical. The SAR analysis provides only the displacement along the direction of the line of sight of the satellite, which is at an angle of about 23° with respect to vertical. and, as consequence, allows a better estimation of the vertical component of the displacement.

GPS methods represent a real advantage with respect to other conventional ground techniques (EDM, topographic levelling, extensometer) for landslide larger than the one studied here in terms of time needed to complete the measurements, precision of the collected data.

The single-frequency GPS equipment used in this study is appropriate for monitoring landslides affected by relatively large displacements.

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