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Using the Global Positioning System to monitor dynamic ground deformation networks on potentially active landslides

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ABSTRACT

The Global Positioning System (GPS) has many advantages over conventional surveying for landslide disaster prevention and mitigation. Once an initial baseline network of ground markers has been positioned, the re-occupation of survey stations determines ground deformation. This verifies both the boundary of the landslide block and ground surface changes. These changes may take the form of either slow to moderate creep, or massive structural failure. Creep may occur as a precursor to slope failure, either within (i) fresh slopes that do not show any evidence of past collapse, (ii) the existing active landslides and (iii) areas adjacent to existing collapses. Networks are measured using rapid static GPS. The method, which enables many survey stations to be measured in a short time, provides a quick means for determining the three-dimensional map of the ground surface (of the landslide). A study in Gran Canaria, Canary Islands, established an initial baseline network within the Barranco de Tirajana, a basin on Gran Canaria that contains evidence of both ancient and recent landslides. Reoccupation of the network using rapid static GPS revealed a field accuracy of approximately 10 mm; the data indicated that the most recent landslide is currently stable.

INTRODUCTION

The use of the Global Positioning System (GPS) for large-scale monitoring of global plate and fault movements has almost taken over from conventional surveying methods [Bock *et al*, 1997; Davies *et al*, 1997; Zumberge *et al*, 1997]. These large-scale networks with very long baselines use continuously recording GPS to obtain a precision of approximately 1-5 mm. Despite the widespread employment of continuous GPS, the use of non-continuous GPS to periodically monitor small-scale ground deformation in place of Electronic Distance Measurement and Leveling is still a relatively new practice. This paper examines the application of GPS to survey areas of less than 10 km^2 that are thought to be undergoing minor ground deformation associated with landslides. Rapid static GPS is used to measure *dynamic ground deformation networks*, which are defined here to be networks of survey stations situated within unstable environments. These networks are monitored over time to detect ground surface changes. The key concept of the dynamic ground deformation network is that the user is looking for changes in the position of semi-temporary survey markers in the form of coherent patterns. The discovery of such patterns then determines the spatial expansion of the network and modifications in the period of time between occupations. Thus the network develops and evolves with the process under investigation. This flexible approach depends upon the easy expansion of the network using semi-temporary survey markers and the versatile GPS technique. The rate of displacement may range from very minor deformation of < 6mm to large-scale deformation of a few meters. However, the significance of these movements depends upon the length of time between occupations. The network is fixed relative to stable or static observation points that are incorporated into the network.

GPS monitoring is being increasingly used in geo-hazard applications. Initially it was primarily applied to broad-scale networks. However as GPS hardware and software has developed, flexible dynamic ground deformation networks have been established. In recent years GPS has taken over the monitoring of volcano-related deformation in Iceland [Foulger *et al*, 1987; Sigmundsson, 1996], Hawaii [Delaney *et al*, 1987], Japan [Shimada *et al*, 1990; Kimata *et al*, 1991] and for Etna, in Italy [Briole *et al*, 1992]; Nunnari & Puglisi, 1994, 1996; Moss, 1999]. Volcano-related landslide research incorporating a comparison of conventional Electronic Distance Measurement (EDM) surveying and GPS was undertaken on the Cumbre Vieja Volcano in La Palma, the Canary Islands, from 1994 to 1998. Moss and co-workers successfully modified the existing EDM network into a GPS network. EDM and GPS techniques were tested against each other and the results revealed similar accuracies, although the EDM exhibited greater errors for baselines that had large vertical differences. A third reoccupation of the Cumbre Vieja GPS network revealed a position repeatability of approximately 10-20 mm [Moss *et al*, 1999]. Similar application of GPS was first used on active landslides in Nuta-Yohue and Taguchi areas, Japan [Sokobiki *et al*, 1995; Fukuoka *et al*, 1995; Kodama *et al*, 1997]. The authors used small-scale GPS networks to examine annual slope velocities in comparison with extensometers; the results indicated that GPS is a viable alternative to other commonly used monitoring strategies. This paper introduces a different approach, using non-permanent GPS receivers to periodically measure a network of survey stations situated over an unstable area that is changing and growing.

A thorough description of GPS and its application is given by Hofmann-Wellenhof *et al* [1997] and Blewitt [1997]. However, explanation of the specific features of GPS is required to justify its suitability for a non-permanent network. The GPS survey method used in this study is *Rapid Static Surveying*. Its aim is to determine the baseline between two nodes of a network in as short a time as possible using a second reference receiver for differential corrections. Short occupation times are possible due to the use of dual-frequency receivers and a 'unique' processing technique developed by Leica Geosystems that calculates the baseline solution as soon as the integer ambiguities are fixed. Fast resolution is possible due to a statistical algorithm that only uses data that fit within its set criteria. Network data are then adjusted using three-dimensional least squares network adjustment: this procedure geometrically computes all the line lengths of the network in order to verify the precise spatial distribution of the survey stations within the network. The field accuracy of rapid static surveying is approximately 5-10 mm ± 1-2 ppm . The precision of a survey is a statistical measure of repeatability, which can be defined as the capability of the technique to consistently measure a single location. Precision will depend upon the technique used. However this computed value may be inaccurate, since accuracy is measured by the closeness of the *measured* value to the *true* value, albeit that only when the *true* value is known can the accuracy be determined.

A principal advantage of GPS in this application is that line-of-sight is not required between survey stations, which means that larger areas can be covered with fewer intermediate survey stations. Non-reliance on line-of-sight also enables the use of both long and short baselines, which facilitates connection with adjacent WGS84 benchmarks (where available), although dense tree canopy can block satellite signals to the GPS receiver. As GPS uses ranges to satellites rather than adjacent survey stations, the satellite geometry at the time of observation becomes more important than network geometry.

Despite the fact that GPS is marketed as an all-weather system, monitoring was temporarily abandoned on Mt. Etna in 1997 and on the Cumbre Vieja network in 1997 due to lightening storms and high winds that produced antenna vibrations [Moss, 1999]. Further problems were encountered when using continuous GPS to monitor the Taguchi Landslide as data revealed a degradation of precision which correlated with periods of heavy snowfall [Fukuoka *et al,* 1995]. However, teams working in other areas prone to heavy snowfall, such as Iceland or Antarctica have recorded no similar degradation.

DESIGN AND INSTALLATION OF THE NETWORK

Before the network is installed and occupied, the area needs to be assessed through a detailed reconnaissance. The reconnaissance commences with the examination of topographic and geomorphological maps of the area to determine the nature and extent of the unstable region. Land-use and the road network are considered to determine the accessibility of the area and it is also necessary to ascertain whether there are any features such as buildings, trees or radio antennas which would impede the use of GPS. Geomorphological features such as steep slopes and scarps with a high aspect ratio are usually found in areas that have either experienced landslides or are likely to produce landslides. This may produce a physical barrier between the GPS receiver and orbiting satellites, thus limiting the number of satellites visible to the user and restricting the positioning of survey stations.

Taking into consideration these issues, the optimal locations for survey stations are marked on the map and the sites are inspected. A good sky view is needed at a potential GPS site to ensure maximum satellite coverage. If this is not good then the satellite almanac is consulted in order to establish the optimal window during daytime during which the maximum number of satellites can be viewed. Each site must be at least five metres from elevated metal structures such as pylons, chain-link fences, corrugated iron roofs or tall trees in order to minimise multipath.

The rapid and often changing patterns of deformation on an active landslide require the use of easily installed, cheap and precise survey markers. Concrete survey pillars are recommended for high precision surveys [Frei & Schubernigg, 1992; Hofmann-Wellenhof *et al*, 1997, p.159], however the rapid physical changes to the ground surface and the size of the unstable area must be taken into account. It is not desirable or economically viable to install a network of 20-40 pillars in an unstable area, especially if many are likely to be destroyed by the landslide process under investigation. The principal markers used are steel survey nails hammered into well-anchored outcropping rocks; they have an indented head for precise set-up (~1-2 mm). In areas with poorly consolidated soil and no rocky outcrops, one-meter-long ribbed metal rods are inserted into the ground with a few centimetres exposed (this end is then marked by luminous tape). The top of the rod has a diameter of 10 mm; using a precise optimal plummet it is possible to set up the tripod within a few millimetres of central point of the marker. Once the survey station marker is installed, the three-dimensional co-ordinate location of these survey stations is measured in order to establish the starting co-ordinates of the network – before it has deformed. This initial occupation provides the *baseline data*. The network is then measured periodically to determine the change from the baseline state.

The key to designing and establishing a GPS network on an actively sliding area is to select survey station positions which will give an accurate representation of the slope velocity. Figure 1 illustrates the typical geometric design of a landslide network that combines both GPS and EDM monitoring techniques on an existing slide. This example is used to highlight the advantages gained by using more than one method. A combination of GPS and EDM benefits from the advantages of each technique, as the EDM may be used in areas of potential multipath, such as those with dense tree coverage, or where continuous or near continuous monitoring is advantageous (since it is cheaper to install and run). In this example, GPS is used to monitor potentially unstable ground around an active landslide, while permanent EDM reflectors are installed on the active part of the landslide to continuously monitor its velocity. The whole network is fixed relative to an International GPS Service (IGS) benchmark – whose position in WGS84 is accurately known – or other fixed benchmarks such as national survey stations, which may also be used if their location is known to within one metre. GPS station velocity and the line length changes between each survey station are analysed over time to assess ground deformation within the active landslide and along its boundaries.

FIGURE 1 A combined GPS and EDM network spanning a landslide, fixed relative to an IGS benchmark.

If the network is established in an area that has not as yet undergone a landslide event, the monitoring network must be large enough to encompass the whole of the cliff or slope that potentially may become unstable. The boundary of the potential landslide should be defined by geomorphological mapping and primary signs of failure, such as soil creep or the formation of faults or scarps.

The geometry of the network and the least-squares adjustment of the calculated positions determine the precision of the data. This precision is degraded by errors in the antenna and its set-up over the survey station. Although the whole network may be precise, the actual survey stations may not be accurately positioned to facilitate re-occupation, therefore the network is married to at least one stable reference station.

TYPES OF GROUND DEFORMATION ASSOCIATED WITH LANDSLIDES

There are many different stages of deformation during the landslide process and these depend upon the type of landslide occurring and the mechanism [Varnes, 1980]. Creep on the unstable hillside is often associated with the early stages of landslides. Slow creep occurs until the point of catastrophic failure or re-gained equilibrium; the rates of movement depend upon the nature and operation of the landslide. Very precise ground deformation monitoring is required to recognize small rates of very slow to slow creep, which may be in the order of 5-10 mm per year. Once recognized, the type of creep can be categorized as (i) primary creep, decelerating from a failure event, (ii) secondary creep, steady slow deformation, and (iii) tertiary creep, accelerating to the point of failure [Varnes, 1980].

A landslide may develop back into a hill, enveloping the ground adjacent to the active landslide. Therefore the boundary between the active landslide and the surrounding area may not be very well defined. Typical characteristics by which the edges of the active area may be defined may include, (i) pressure ridge formation at the head or toe, (ii) fractures at the head or toe, or crevasse-style cracking over breaks of slope, (iii) spreading at the toe, (iv) small normal faults at the crown that form scarps, and (v) soil creep [Dikau *et al*, 1997]. Analysis of deformation data provides a model of landslide development and growth, thus identifying the principal direction and rate of movement. Figure 2 illustrates a typical deformation pattern that may be recorded from the network example introduced in Figure 1. Displacement patterns reveal differences in the rate and magnitude of deformation for three distinct areas, (i) the middle of the active landslide, (ii) the unstable area adjacent to the landslide and (iii) the stable area.

The stable area in Figure 2 reveals very small changes that do not follow any coherent pattern. These negligible movements reflect minor errors in the measurement of the survey station due to satellite signal reception and are typically within the error margins of the technique. The area adjacent to the landslide shows displacements normal to the direction of slope and it is often characterized by the creation of ridges and scarps through minor, steady deformation of 2-10 cm per year. This pattern of deformation indicates that the right side of the landslide is deforming at a greater rate than the left side. It may therefore be assumed that the right side is even more unstable and may potentially become part of the active body of the landslide. Failure time-scales depend upon specific site conditions and landslide mechanisms.

The highest level of deformation is recorded in the most active part of the landslide. In Figure 2 this is in the centre of the landslide body. Orientation of this movement defines the current principal direction of the landslide, and rate of deformation depends upon the style of landslide. For example, a debris flow may occur with a rapid or extremely rapid velocity of 3-5 m per minute during activation, while a slow velocity block slide may deform at a velocity of <1 m per year.

APPLICATION OF GPS SURVEYING TO POTENTIALLY ACTIVE LANDSLIDES

The techniques discussed in this paper have been applied to two recognised landslides. The application of the technique to the Barranco de Tirajana, Gran Canaria, will be examined in detail, illustrating the measurement procedure and the determination of the baseline network coordinates. In order to illustrate the effectiveness of the monitoring element of the technique, its application to the active Tessina Landslide in Northern Italy will then be briefly considered.

FIGURE 2 An example of deformation that may be recorded from the geodetic network illustrated in Figure 1.

BARRANCO DE TIRAJANA, GRAN CANARIA

Barranco de Tirajana is a wide river valley situated in the central-southern sector of Gran Canaria. It is approximately 5 km wide and 12 km long, forming an amphitheater-shaped valley that opens towards the sea and is surrounded on three sides by kilometer high cliffs. The Tirajana River runs through the Barranco, fed by numerous minor tributaries; the riverbed is usually dry.

Barranco de Tirajana contains 28 principal landslides, the oldest of which was emplaced at least 52,000 years ago The landslides comprise both deep rotational or block slides and debris slumps and slides [Lomoschitz & Corominas, 1992]. Recent movements have concentrated on the centre of the Barranco de Tirajana, in Rosiana. The first recorded activity of the Rosiana landslide was in 1879, when the material was mobilised after a period of heavy rain. More recently, in 1956, after a period of exceptional rainfall (272 mm in 24 hours), three million cubic meters of material was displaced, three hundred people had to be evacuated, and several homes were destroyed. Recent measurements of survey pillars, adjacent to a bridge destroyed in 1956, suggest an annual creep-rate of 1 cm per year. As bi-annual occupation of a GPS network is capable of detecting creep rates of 5-10 mm, continued monitoring using GPS should identify coherent patterns of deformation to determine (i) the exact boundaries of the Rosiana landslide and (ii) the precise magnitude of annual creep.

Design and establishment of a dynamic ground deformation network

Twenty-five survey stations have been installed over the whole of the upper Barranco de Tirajana in order to monitor large scale movements across the valley; eight of these survey stations are located in the Rosiana area (Figure 3). To maximize the amount of data and act as a double-check for the detection of movement, survey stations were installed in pairs in areas thought to be prone to current landslide-related deformation. A combination of steel survey nails and metal rods were used as survey station markers. To increase efficiency and accessibility, the stations were located near to the main road passing through San Bartolomé, Rosiana and Santa Lucia, and other minor roads leading off it. Unfortunately, although the valley is not densely populated or covered with trees, there are a number of objects that cause multipath, including; (i) metal electricity pylons with overhead wires

FIGURE 3 Barranco de Tirajana GPS network.

and (ii) chain link fences. Although multipath is less of a problem for dual frequency receivers, which use both phase and code processing, it is prudent to avoid locating them in unfavorable sites. The co-ordinates of four of the seven survey stations within the Rosiana area form the brace of the EDM network [Quintana & Lomoschitz, 2000].

Data collection and results

The first stage of data collection was to fix the network to a stable local survey station. This could have been done in two ways: (i) fixing a station within the network, and (ii) using a local benchmark whose co-ordinates are known in WGS84. The first method uses a survey station situated in a stable area within the network. Data recorded during the length of the campaign is processed as a single static point and the approximate position is determined from the mean of the results. The second method is preferred as the survey station is fixed to a known benchmark. However the accuracy degrades as the baseline length increases between the network and the benchmark, so that if the distance of baselines to the stable benchmark is more than 20 km then the first method is used. There is an IGS benchmark (MAS1) 18.7 km from the Barranco de Tirajana network. Therefore the second method was used.

Three survey campaigns have been undertaken on the Barranco de Tirajana network. The first occupation was undertaken during network installation in March 1998. Survey stations were positioned relative to the local reference station located at Hot13 (on the roof of the local hotel in San Bartolomé). Although the survey station is not considered stable in the long term, due to its roof top location, site security creates an ideal base station because it can be left unattended. During each survey the data from Hot13 was fixed with reference to MAS1 by single baseline processing using SKI2.2 software developed by Leica. Figure 4 illustrates the variation in the position of HOT13 calculated from MAS1 and shows the fixed co-ordinate obtained. Data were collected for 12-hour periods for two days in March 1998 and six days in November 1998. The results show a variation of less than 30 mm on the horizontal plane and less than 50 mm on the vertical plane. Once the network is located in WGS84, the IGS benchmark or local stable survey stations may be held fixed between survey campaigns to integrate the surveys.

Three survey campaigns have been undertaken on the Barranco de Tirajana network. The first occupation was undertaken during network installation in March 1998. Survey stations were positioned relative to the local reference station located at San Bartolomé (Hot13).

Least squares analysis of the data (confidence level of 68 percent) revealed an average error ellipse of 8.3 mm on the semi-major axis, 7.1 mm on the minor axis and 12.7 mm in height. The initial station co-ordinates and their standard deviations are listed in Table 1. Second and third occupations of the network were undertaken in November 1998 and April 1999 and followed the same procedure. The hotel was used as the principal base station. These surveys produced slightly better error ellipses, although a few poorer results (15-20 mm) were recorded for three or four individual positions. These inferior posi-

FIGURE 4 Movement vectors indicating the positioning of the point Hot13 relative to MAS1 for six consecutive days in November 1998. Changes in the (a) horizontal and (b) vertical plane.

FIGURE 5 Vector displacements in the Barranco de Tirajana GPS network between November 1998 and April 1999.

tionings (reflected in the error ellipses and standard deviations) are the result of poor repeatability between individual satellite ranges, and are thought to be due to multipath or other factors which may affect signal strength and reception.

Figure 5 illustrates the survey station velocity between the November 1998 and April 1999 data sets. Although the figure appears to show 'displacement' the results are all *insignificant*. The determination of significant and insignificant data is quantified by examining the data against field operating errors (Table 2), error ellipses and the standard deviations of both data sets. The few vectors in Figure 5 which exceed 30 mm all have poor standard deviations (in one or both data sets), which may be attributed, as mentioned above, to multipath or other signal degrading factors. A further confirmation of the insignificance of the data is that changes in survey station position between November 1998 and April 1999 do not form coherent patterns. This lack of coherency is especially important when assessing the deformation of the survey station pairs, as they clearly do not show similar vector azimuths. The results of the Barranco de Tirajana network therefore indicate that there had been no significant deformation within the valley. Due to the lack of deformation at the Barranco de Tirajana, this technique will also be briefly examined with reference to a highly active landslide at Tessina, Northern Italy, in order to validate its application as a ground deformation monitoring technique in very unstable areas. As the methodology applied was similar to the Barranco de Tirajana, a brief account of the network will be given and a report of the results.

TESSINA LANDSLIDE, ITALY

The Tessina valley is located in Italy approximately 80 km north of Venice. The valley contains a complex landslide that has been the source of nine major reactivations since 1960. In 1998 a GPS ground deformation network was established over the active Tessina Landslide to determine the rate of deformation around the crown of the rotational failure and the potentially stable area beyond this active zone. The Tessina landslide is a complex landslide, divided into an upper rotational slide and a lower flow. Rotational landslides form around the detaching zone. There are numerous small scarps (0.5-2 m high), which are the head walls of multiple small rotational collapses. They are activated by high rainfall that saturates the clay layers within the flysh formation, increasing pore fluid pressures. These separate bodies descend into the upper accumulation zone, where the amassed material is mobilized by the active spring, thus forming mudflows, which continue downwards through the connection canal. Using the methods already described in this paper, a 22-survey station GPS network was installed in July 1998. This was reoccupied in July 1999 and October 1999 using a permanent GPS benchmark located in Graz, Austria, as the stable benchmark, which was held fixed between surveys.

The results reveal substantial ground deformation associated with the rotational landslides. Analysis of these data are still going on, but preliminary data show lateral displacements of up to 9 m and vertical displacements of up to 1.5 m. The landslide can be divided into three sections: western, eastern and central. The western section is the most active and contains the largest movements, which are all oriented to the direction of maximum slope. The displacements reveal a discrete body bounded by an older fault that has become reactivated and displaced approx. 1-1.5 m downslope. The central area is also unstable but appears to have undergone more steady continuous creep in the order of 0.5-1 m downslope. The eastern section, which in the past has proven the most active area, reveals less deformation; the survey stations, however, extend further back from the edge of the scarp. The results suggest that the next major movement is most likely to originate from the unstable western flank, where a section of the flank is bounded by an active fault. Periodic monitoring suggests that although substantial movement of 9 m may have been confined to a single deformation event or series of events, the displaced block is still deforming at a rate of 2-3 cm down slope a month. The landslide appears to be undergoing near constant displacement and a rotational slip from the western flank may occur during the next year or two.

CONCLUSIONS

1. The rapid static GPS technique, used either as a stand-alone technique or in conjunction with EDM, provides a valuable method for monitoring areal extent and development of landslide processes.

2. A baseline network in the Barranco de Tirajana, Gran Canaria, Canary Islands, has been successfully established using a combination of EDM and GPS

3. Reoccupation of the Barranco de Tirajana network after one year has revealed only negligible displacements that do not form coherent patterns. The technique is technically accurate to 10-15 mm but poor field conditions may result in a repeatable precision of 25-30 mm.

4. The establishment of a GPS network at Tessina, Italy, has revealed major displacement associated with the active landslide. Periodic measurements have revealed the rates of movement and have indicated the areas that are most likely to fail.

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RÉSUMÉ

Le système de positionnement global (GPS) a plusieurs avantages par rapport aux méthodes de levé conventionnel pour la prévention et la limitation d'une catastrophe due à un glissement de terrain. Quand on a établi un réseau de points fixes au sol, la remise en station sur ces points permet de déterminer la déformation du terrain. Ceci vérifie à la fois la limite du bloc de glissement de terrain et les changements de la surface du terrain. Ces changements peuvent prendre la forme soit d'un glissement modéré ou d'une catastrophe structurelle massive. Un glissement peut se produire comme précurseur d'instabilité de pente, soit au sein (i) de talus frais qui ne montrent pas d'évidence d'affaissement, (ii) de glissements de terrain actifs existants et (iii) de zones adjacentes à des affaissements existants. Des réseaux sont observés en utilisant un GPS en mode statique rapide. La méthode, qui permet d'observer plusieurs points de station dans un temps court, fournit un moyen rapide pour déterminer une carte tridimensionnelle de la surface du terrain (du glissement de terrain). Une étude dans les îles de Grande Canarie a établi un réseau initial dans la zone de Barranco de Tirajana, un bassin dans la Grande Canarie qui montre des traces de glissements de terrain anciens et récents. Une nouvelle observation des points du réseau utilisant la méthode GPS en mode statique rapide a donné une précision sur le terrain de 10 mm, les données ont indiqué que le plus récent glissement de terrain est actuellement stable.

RESUMEN

El Sistema de posicionamiento global (GPS) tiene muchas ventajas con respecto a latopografía convencional para la prevención y mitigación de los desastres por corrimientos de tierras. Una vez que se ha ubicado una red de referencia inicial de marcadores sobre el suelo, la nueva ocupación de las estaciones de reconocimiento determina la deformación del suelo. Esto verifica tanto el límite del bloque del corrimiento como los cambios en la superficie del suelo. Estos cambios pueden ser en forma de deslizamientos lentos a moderados o bien como fallos estructurales a gran escala. Se pueden producir deslizamientos como precursores del fallo de la ladera, ya sea en (i) laderas nuevas que no muestran evidencias de antiguos derrumbamientos, (ii) los corrimientos de tierras activos presentes y (iii) áreas adyacentes a derrumbamientos ya existentes. Las redes se miden empleando GPS estáticos rápidos. El método, que hace posible que se puedan medir muchas estaciones de vigilancia en poco tiempo, proporciona un medio rápido para determinar el mapa tridimensional de la superficie del suelo (del corrimiento de tierras). Un estudio realizado en Gran Canaria, islas Canarias, estableció una red de referencia inicial en el Barranco de Tirajana, una cuenca de Gran Canaria que contiene pruebas de corrimientos de tierras tanto antiguos como recientes. La reubicación de la red mediante GPS estático rápido reveló una exactitud del campo de aproximadamente 10 mm; los datos indicaron que el corrimiento de tierras más reciente es estable en la actualidad.

TABLE 1 Baseline network co-ordinates for the Barranco de Tirajana network

Survey Station	*Longitude N*	*Latitude W*	*Ellipsoid Height (m)*
hot13	27 55 27.428 fixed to MAS1	15 34 23.72945 fixed to MAS1	947.240 fixed to MAS1
rab16	27 53 23.579075±0.0071	15 32 06.009485±0.0075	567.8258±0.0182
ant20	27 53 21.006757±0.0037	15 32 56.106489±0.0062	646.5254±0.01231
bbb14	27 55 38.591141±0.0042	15 32 47.334445±0.0051	930.1770±0.01456
bir22	27 56 32.904409±0.0048	15 32 25.028755±0.0057	1642.409±0.01162
cem15	27 53 01.040200±0.0058	15 31.47.696820±0.0069	541.4954±0.01325
flw18	27 54 56.566811±0.0039	15 33 59.740021±0.0034	824.3694±0.00954
frd2	27 56 08.325971±0.0032	15 33 06.127662±0.0033	1038.292±0.00891
gra4	27 56 14.587934±0.0035	15 34 50.685722±0.0034	1108.988±0.00852
gwy24	27 55 30.675574±0.0038	15 32 50.964375±0.0035	953.7031±0.00946
liz12	27 55 40.021862±0.0031	15 34 37.101332±0.0031	994.0808±0.00922
per10	27 57 04.269843±0.0037	15 31 22.119652±0.0038	1574.671±0.00576
maj3	27 56 27.398623±0.0028	15 34 03.607118±0.0028	1180.402±0.00887
man23	27 54 18.558116±0.0047	15 32 57.194875±0.0057	576.9912±0.01342
oni6	27 54 12.861413±0.0051	15 32 13.475975±0.0059	686.9243±0.01127
p23	27 55 11.592077±0.0030	15 33 07.136122±0.0036	694.8443±0.00823
p31b	27 55 23.286393±0.0050	15 33 05.472132±0.0038	778.8612±0.01238
p36	27 55 11.912858±0.0044	15 33 25.515185±0.0038	748.4476±0.01001
p51	27 55 06.222538±0.0052	15 32 56.370356±0.0051	729.3846±0.01521
per5	27 55 40.518209±0.0029	15 34 35.905366±0.0027	989.4192±0.00794
pip17	27 54 59.437541±0.0038	15 34 06.373497±0.0036	855.9657±0.00865
rai8	27 56 27.064846±0.0030	15 34 03.094098±0.0027	1180.899±0.0085
res7	27 53 18.715793±0.0039	15 32 03.140587±0.0052	537.6818±0.01069
rid11	27 55 43.358000±0.0037	15 35 52.875473±0.0042	1315.242±0.00828
sle19	27 53 11.415089±0.0050	15 33 03.389477±0.0063	665.1367±0.01128
tan25	27 55 30.412800±0.0035	15 32 50.598169±0.0033	956.6690±0.01241
tom26	27 54 18.441734±0.0046	15.32.57.883684±0.0057	575.7886±0.01151

TABLE 2 Estimations of the accuracy of the EDM and GPS techniques used with a tripod/tribrach set-up in the field [Burnside, 1991]

Sokkia Set3c Total Station	*Type*	*Estimated error*
Distance measurement error	Random	5mm + 5ppm
Vertical angle measurement	Random	±3'
Temperature 1 º C variation	Random	1-2ppm
Pressure 3mmHg variation	Random	1-2ppm
Setting up error	Random	2-4mm
Internal instrument errors	Systematic	unknown
Prism pointing	Random	+/- 0.5-1mm
Total		**6mm + 5ppm**
Leica 399		
Rapid static GPS (broadcast ephemeris)	Systematic	5mm + 1ppm
Set-up errors	Random	<4mm
Unmodeled tropospheric variation	Random	2ppm
Total		**6mm + 3ppm**