ISSN 2047-0371

2.1.3. dGPS

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ABSTRACT: Direct acquisition of elevation data is an important aspect of many geomorphological studies, particularly those which include mapping of features, or investigation of topographic change. Differential global positioning systems (dGPS) provide an accurate and efficient method of obtaining elevation data, and have been used in a range of environments. The basic methodology for conducting a dGPS survey is summarised, followed by discussion of a range of adaptations to the basic system to enhance productivity. Finally, the possibilities for integrating dGPS with other methods are considered. dGPS is an accurate and versatile geomorphological tool, and can be used successfully either as a stand-alone method for surveying, or in conjunction with other methods.

KEYWORDS: dGPS; surveying systems; surface morphology; terrain; topography

Introduction

Global positioning systems (GPS) calculate the transmission time of messages received from GPS satellites to provide information on their location, accurate to ~ 15 m. Improvements in technology and a requirement for greater accuracy led to the development of differential global positioning systems (dGPS) during the late 1980s (McCoy, 2005). The greater accuracy is due to use of a base station and roving receiver. The base station is positioned at a location with known coordinates, and continually records its position according to the satellite network. Corrections based on the base station's internal calculations are applied to the position data selectively recorded by the roving receiver, increasing accuracy to the cm level. For standard dGPS equipment these corrections are applied during the data processing stage, but real time kinematic dGPS stations are able to apply corrections as locations are recorded, providing an immediately available quality check.

In geomorphology, dGPS has been used for surveying and mapping since the 1990s (McCoy, 2005). Initially, it was mainly employed to provide control points for other surveying techniques. However, since the mid-1990s dGPS has been used as a surveying method in its own right (Baptista *et al*., 2008), offering advantages in the speed and density of data collection (Harley *et al*., 2011). The high accuracy of dGPS made it possible to conduct short-timescale studies of small morphological changes (Mitasova *et al*., 2003; Pardo-Pascual *et al*., 2005; Harley *et al*., 2011).

Since the early 2000s, dGPS has been adopted as one of the most common surveying tools in geomorphology. It has been used extensively in a wide range of environments (Table 1). The simplest application of dGPS involves recording the location of features or points of geomorphological interest, for example, the highest points of dune crests (e.g. Mitasova *et al*., 2005). For small features a single dGPS reading may be sufficient, but for larger features it is also possible to take a series of points. The form of these is dependent on the feature being measured, but may be linear such as shorelines (e.g. Rocha *et al*., 2009), or situated around the external edges of a feature, e.g. a pond. The end purpose of this application is normally to create new maps, or enhance existing ones with the addition of extra features. Where the surface morphology of an area rather than a feature is of interest, dGPS can be used to conduct topographic surveys of the entire area. dGPS surveys are capable of recording data in three dimensions (latitude, longitude, and elevation), and may be used for 2- or 3-dimensional mapping.

Table 1. Examples of studies using dGPS in a range of environments.

Environment	Example publications
Dune field	Mitasova *et al*., 2005; Navarro *et al*., 2011
Littoral	Mills *et al*., 2005; Suursaar *et al*., 2005; Baptista *et al*., 2008; Rocha *et al.,* 2009; Yang 2010; Bertoni and Sarti, 2011
Agricultural land	Saha, 2003; Zhang *et al*., 2011
Salt marsh	Chassereau *et a*l., 2011
Forest	Hartvich and Mentlik, 2010
Floodplain	Casas *et al*., 2006
Volcanic	Gomez *et al*., 2009; Onderdonk *et al*., 2011
Fluvial	Ujvari *et al*., 2009
Landslide	Malet *et al*., 2002; Corsini *et al*., 2005; Glen *et al*.; 2006 Baldo *et al*., 2009
Glacial	Quincey *et al*., 2009; Serrano *et al*., 2010; Zhang *et al*., 2010

dGPS survey data is commonly imported to geographic information systems (GIS), where linear points can be converted to lines and survey points to digital terrain models (DTMs). This use of the data makes it possible to compare collected data to other datasets, which may have been collected by dGPS or other methods, e.g. photogrammetry, light detection and ranging (LiDAR), or digitised maps. Repeat surveys of the same areas or features can be compared, making dGPS a powerful tool for measuring morphological changes over short, medium and long timescales (e.g. Malet *et* al., 2002; Baptista *et al*., 2008; Ujvari *et al.*, 2009; Bertoni and Sarti, 2011; Harley *et al*., 2011). The change measured is dependent on the data acquired. Linear data can be used to track the movement of features, e.g. Bertoni and Sarti (2011) conducted repeat surveys of shore-normal beach profiles, and tracked the distance of retreat of features such as berms. If survey data is interpolated to create a DTM, changes in volume can be calculated using raster subtraction between surfaces (e.g. Baptista *et al*., 2008; Harley *et al*., 2011).

A further use of dGPS in geomorphology is to determine the accuracy of other survey methods. Accuracy is dependent on the equipment set-up used (Table 2), but can be reduced to 1-3 cm by increasing point occupation times and processing results using data from the GNSS (Global Navigation Satellite System) network (Landau *et al*., 2008). This compares favourably with other survey methods, being similar to terrestrial laser scanning (TLS) accuracy (Dornbusch, 2010), and more accurate than airborne LiDAR (highest achievable accuracy ~0.1-0.2 m, e.g. Sallenger *et al.*, 2003). Additionally, dGPS accuracy is not significantly reduced by environmental factors. However, some survey methods, such as LiDAR can gather data more rapidly.

dGPS points may be used to determine the error associated with other techniques due to their high accuracy (e.g. Baldo *et al*., 2009; Harley *et al*., 2011; Zhang *et al*., 2011). After comparing surveys of a salt marsh conducted using dGPS and LiDAR Chassereau *et al*. (2011) found LiDAR to be sufficiently accurate over most of their study area, but recommended the use of dGPS where microtopography or small morphological changes were important. For the above reasons, dGPS may be used in conjunction with other survey methods, as well as functioning as a stand-alone survey technique.

Table 2. Accuracy and productivity of different methods of conducting a dGPS survey. Note that values given are indicative of some of the highest achievable rates on beach terrain. Surveys on more complex terrainare likely to take longer to complete.
[1] Baptista et al., 2008; [2] Pardo-Pascual et al., 2005; [3] Harley et al., 2011; [4] Baptista et al., 2011.

Method	Foot	Foot	Wheel	Vehicle (1 antenna)	Vehicle (2 antennae)
Mode	Static	Continuous	Continuous	Continuous	Continuous
Accuracy (m)	< 0.05 [3]	~ 0.05 [2,3]	< 0.1 [1]	< 0.1 [1]	< 0.05 [4]
Productivity	< 0.05 [3]	0.5 [3]	10 [1]	100 [1]	100 [1]

Method

Survey design

Before conducting a survey using dGPS it is important to determine what will be surveyed, the density of points required, and the method of surveying. The time and methods available, and the aim of the survey, will dictate the maximum point density and area of coverage. It is important to note that in certain environments the time allocated to a survey may be reduced by the natural characteristics of the site, e.g. tides may limit the time available to survey beaches and estuaries.

When the survey objective is to generate a surface grid, there are three main sources of error to consider when designing the survey, all of which are inter-linked. These are:

i) Terrain morphology: for any given survey duration, it will be possible to map a less complex surface with less error than a more complex surface, i.e. a low-gradient, geomorphologically mature surface may be reliably mapped with less points than mountainous terrain.

ii) Survey point density: Increasing survey point density will decrease error. The higher the number of survey points, the greater the ratio of known elevations to estimated elevations in the surface grid generated.

iii) Interpolation technique used: Many different interpolation methods are available with most commercial GIS. Each one will produce a slightly different surface from the same set of survey points. Error is minimised by selecting an interpolation method appropriate to the survey area and objectives.

Aguilar *et al*. (2005) found that the terrain morphology was the largest source of error, followed by survey point density, with the choice of interpolation method having the smallest effect on surface grid error.

If the area surveyed has little variation in terrain morphology capturing elevation data at a series of points on a regular grid will provide the best results when data is interpolated. However, as variations in surface morphology, and variations in point density affect the error associated with the final product some degree of survey bias may be beneficial, particularly if time is limited and terrain morphology is variable across the survey area. For example, Baptista *et* al. (2008), surveying at a coastal site, examined the effects of varying point density on the surface grid produced. They found that a high point density was required to capture variation on the topographically complex dune surfaces, while the relatively planar beach surface could be accurately mapped with a much lower point density.

To create a surface grid or DTM from point data interpolation or geostatistical methods are used to estimate the area's topography from the measured elevation data. Several different methods are available to do this, including: kriging, natural neighbour, inverse distance weighting, spline, and triangulated irregular network (TIN). Each of these methods makes different statistical assumptions about the data being used. The error associated with an interpolation method can be established by removing some measured points from the analysis and comparing the difference between the estimated and measured values for these locations. A benefit of using kriging is that this process is carried out automatically, and surface error maps can be produced in addition to a DTM. While choice of interpolation method has a relatively minor effect on surface accuracy (Aguilar *et al*., 2005), Baptista *et al*. (2008) found that TIN, spline, and kriging produced results with lower RMS than the other methods in a coastal environment. Additionally, kriging and TIN are exact interpolators, which ensures that where elevation has been measured, this value is used in the resultant surface. Most interpolation methods require an approximately rectangular grid of points which may constrain the area surveyed. Alternatively, points falling outside a rectangular grid may be removed during processing (Dornbusch, 2010), or additional steps can be taken to fit irregularly spaced data to a grid (Harley *et al*., 2011).

A final consideration in designing a survey with the purpose of creating a surface grid or DTM is the 'edge effect'. Edge effects are erroneous results occurring around the boundary of the interpolated area due to a lack of surrounding data to inform estimations. This can be avoided by extending the surveyed area beyond the area of interest, and then clipping the resultant surface grid to the area of interest.

Survey method

The dGPS system consists of a static base station and a movable rover (Figure 1). The rover can be configured in several ways which provide different methodologies for surveying. The simplest configurations involve mounting the roving antenna on a tribrach or pole. These are then positioned over the point to be measured, levelled, and a point is recorded manually (static mode). The time taken to measure points is normally 2-3 minutes when using a tribrach and ~10 seconds when using the pole. In windy conditions points may take longer to measure as the antenna must be held horizontal to minimise errors.

Several authors have proposed and used adaptations to this basic configuration to increase productivity, in some cases at the expense of accuracy (Table 2). These adaptations do not require the operator to manually decide which points to record; instead the rover measures points continually at a set frequency. The most basic adaptation is simply placing the rover antenna in a back-pack and setting it to take continual measurements as the operator walks across the area to be surveyed (Pardo-Pascual *et* al., 2005; Dornbusch, 2010). A further enhancement involves mounting the antenna on a pole attached to a wheel, which can be rolled across the survey area (Buckley and Mills, 2000). The most advanced method mounts one or two antennae onto a rig attached to a moving vehicle (normally a quad-bike) which drives backwards and forwards across the survey area continually collecting data (Baptista *et al*., 2008; Baptista *et al*., 2011). Each of these methods has advantages and disadvantages, which are summarised in Table 3.

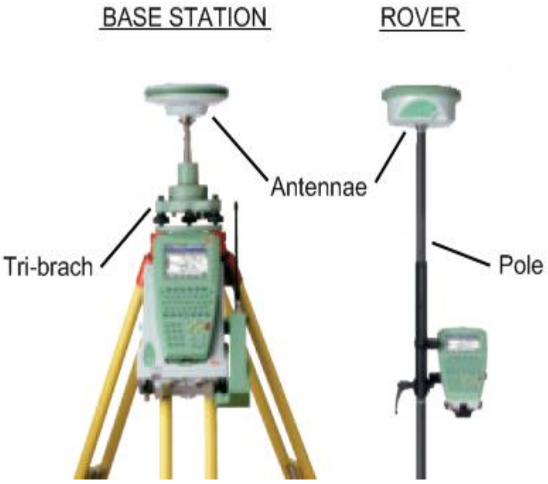

Figure 1. Leica dGPS 1200 system base station and rover with features referred to in the text annotated (adapted from Leica Geosystems, 2008).

Setting up the base station

Before points can be recorded the base station must be set up. The base station does not need to have a line of sight to the survey area, and depending on the dGPS system used, it may be up to a maximum distance of 2 – 10 km from the survey area. However, if surveying alone it is preferable to remain within view of the base station, or within easy access of it for security reasons.

The dGPS base must be level to obtain maximum accuracy. This is achieved by positioning the antenna on a tripod. This enables the base station to be set up on most terrain as the length of each leg can be

Table 3. Advantages and disadvantages of different dGPS survey methods.

Method	Advantages	Disadvantages
Foot (static)	Very high accuracy No modifications to equipment required Point density can be varied Suitable for all terrain	Very low productivity Accuracy and productivity may be reduced in high winds
Foot (continuous)	No modifications to equipment required Points taken automatically Suitable for all terrain	Error introduced as antenna not always vertical (especially on slopes)
Wheel	No expensive modifications required Points taken automatically Suitable for most terrain	Error introduced as antenna not always vertical Wheel may sink into very soft sediments
Vehicle (1 antenna)	Very high productivity Points taken automatically	Expensive modifications required Unsuitable for some terrains (e.g. fragile soils and plants, steep slopes) Vehicle may sink into soft sediments Requires vehicle access Error introduced as antenna not always vertical (especially on uneven terrain)
Vehicle (2 antennae)	Very high productivity High accuracy	Expensive modifications required Unsuitable for some terrains (e.g. fragile soils and plants, steep slopes) Vehicle may sink into soft sediments Requires vehicle access Error introduced as antenna not always vertical (especially on uneven terrain)

individually altered. While relatively stable, in windy conditions it is best to set the base station up on soil rather than concrete or tarmac for additional stability.

If repeat surveys of the same site are required it is preferable to ‘monument’ the position of the base station using a marker, e.g. paint, nails, screws, etc., to ensure that the same position can be returned to. If this is not possible control points at easily identifiable locations can be taken using the rover. These points can then be resurveyed on each subsequent visit, and used to correct for any differences in the position of the base station between surveys (McCoy, 2005).

Full instructions for setting up the base station are included in manuals supplied with the equipment, and are dependent on the make and model of the system. Leica and Trimble dGPS systems are commonly used by geomorphologists and their manuals are available via their websites. The basic procedure common to all dGPS systems involves setting up the tripod on which the other components are mounted. These include the antenna, batteries, the dGPS unit, and the radio (optional) (see Figure 1). The antenna must be mounted on a tribrach to ensure that it is level. The radio is only required if the RTK function is desired.

Once the physical components of the dGPS system are set up, the screen on the dGPS unit is used to start a survey. The exact process depends on the make of the system and is available in the equipment manuals. Generally, this involves naming the survey, entering information about the required equipment configuration, and then setting the dGPS unit to acquire its location. This process takes ~20 minutes, during which time the base station continually receives location data from satellites, which are averaged to give an accurate position for the base station. During this time the rover can be set up. Whether using a vehicle, a pole or a tribrach, the rover set-up will include an antenna, batteries, dGPS unit and a radio antenna if used.

Survey

To conduct a survey the rover's dGPS unit is turned on, and the survey name is entered. If continuous measurements are required the desired frequency of measurement is entered, and the operator simply moves across the survey area while points are automatically recorded. If static measurements are required each point must be individually 'occupied'. This involves pressing a button the dGPS rover unit and waiting for the point to be recorded before moving to the next point and repeating this procedure. Maximum accuracy is obtained by using the bull's eye spirit level connected to the antenna pole or tribrach to ensure the instrument is level while the point is occupied. Occupation time depends on whether the rover is mounted on a pole or tribrach, and the make of the system, taking on average 2-10 seconds, and between 30-180 seconds, respectively.

The path taken by the surveyor across the area of interest will be dependent on what the aims of the study are, what features are to be included in the survey, how much time is available, and the degree of coverage needed. To maximise efficiency Baptista *et al*. (2008) suggest planning the survey as a series of transects designed to capture areas of maximum variation. In their beach study most variation was cross-shore rather than long-shore, so transects could be widely spaced along the shore provided that points were densely spaced along each transect.

When sufficient points have been recorded the survey is stopped using the dGPS unit. Data is saved automatically onto CF cards in the unit.

Repeat surveys

For some studies it may be necessary to resurvey the same locations to measure changes in elevation, e.g. ground bulging in volcanic areas (e.g. Nishi *et al*., 1999; Lagios *et al*., 2005). Resurveying the same locations can be achieved by installing benchmarks or using the 'stake-out' function of the dGPS system. To use this function the original survey coordinates must remain stored on the dGPS CF cards. The exact method for using stake-out depends on the make of the dGPS system, but involves the location of past survey points being displayed on a mini-map on the roving dGPS unit's screen. The map displays the position of the location to be resurveyed and the position of the roving receiver, making it possible to navigate to the point(s) of interest.

Processing

Discussion of the full data processing method is beyond the scope of an article on the direct acquisition of raw data. However, a few simple steps are required to transfer the survey data to a computer in a usable format. These involve copying the data from the CF cards to a computer's hard-drive. Once on the hard-drive the data can be processed using software provided by the manufacturer. The result is a table which includes information on each point acquired, such as the time recorded, coordinates, elevation, and quality. The table can be copied into a text file or a spreadsheet, ready for further processing.

Error

The accuracy associated with using different methods to conduct dGPS surveys has been discussed above, but there are some additional sources of error which should be considered. Some of these cannot be directly controlled, such as the number of satellites the dGPS can receive position data from. A minimum of four satellites are required to provide a vertical and horizontal dGPS position (Leica Geosystems, 1999), and a minimum of six satellites are required for RTK-dGPS (Pardo-Pascual *et al*., 2005). The more satellites the dGPS can receive data from, the higher the accuracy of the position obtained. This is dependent on the position of satellites above the earth, and varies as they move through their orbits. If surveying in a built-up area, below cliffs or in a forest, the accuracy will be reduced as trees, buildings and cliffs will block some of the satellite signals (McCoy, 2005).

Preventable sources of error have already been mentioned and include deviation of the rover antenna from the vertical and failure to use control points for repeat surveys. Human sources of error, and best practice to avoid them, are dependent on the survey method and are summarised in Table 4.

Table 4. Sources of error associated with each dGPS method and suggestions to minimise them. *[1]Baptista et al., 2008; [2]Dornbusch, 2010; [3]Harley et al., 2011.*

Method	Sources of error	Best practice to prevent errors
Foot (static)	Pole or tribrach may sink in soft ground	Ensure pole/tribrach is held with point resting at surface level OR Place a mark a set distance from the base of the pole and ensure pole is always sunk into ground to level of mark
Foot (continuous)	Antenna not physically connected to ground[1]	N/A
	Variation in height due to walking[2]	Will cancel out over course of survey provided measurements not synchronous with steps[2]
	Change in antenna height when walking up slope or adjusting backpack[2]	Set up a series of control points and check these regularly throughout survey[2]
Wheel	Wheel will change point of contact on beach when on slope[2]	Use smallest wheel size possible[2]
Vehicle (1 antenna)	Vehicle sinking into ground	N/A
	Mast with antenna deviates from vertical due to roll and pitch (particularly on slopes)[1]	Restrict use to relatively flat surfaces OR use 2-antenna configuration[1] OR on smooth surfaces error may be within accuracy of dGPS[1]
Vehicle (2 antennae)	Vehicle sinking into ground	N/A
	Mast with antenna deviates from vertical due to pitch[1]	A 3rd antenna can be incorporated[1]

Integration of dGPS with other methods

Alternatives to dGPS for acquiring elevation data include total station, LiDAR, TLS, and stereophotogrammetry. The advantages and disadvantages of these techniques are detailed in Table 5. The most appropriate method for any survey will be reliant on a number of factors including: time available; accuracy required; survey area; cost; and, terrain.

The techniques listed in Table 5 need not be used in isolation. The variation in accuracy and productivity between techniques has led to a number of studies which use multiple techniques to obtain datasets covering a survey site at a range of scales and resolutions. This makes it possible to investigate changes at small, medium and large scales, spatially and temporally.

Some of the techniques listed in Table 5 are relatively modern. To investigate geomorphic change over longer time periods than the last couple of decades, data obtained using older surveying techniques, or extracted from historical aerial photography and maps, may be combined with modern survey data to provide a more continuous record of change (e.g. Yang *et* al., 2010; Harley *et al*., 2011). Additionally, dGPS may be used to ground-truth the accuracy of lower accuracy, higher productivity techniques like airbone LiDAR (e.g. Saha, 2003; Baldo *et al*., 2009; Hofle *et al*., 2009; Chassereau *et al*., 2011; Zhang *et al*., 2011).

Table 5. Advantages and disadvantages of techniques for acquiring elevation data. [1]Pardo-Pascual et al., 2005; [2]Harley et al., 2011; [3]Dornbusch, 2010; [4]Gregory and Goudie, 2011.

Method	Advantage	Disadvantage
dGPS	High accuracy Range of methods have been developed to suit different surveying requirements Line-of-sight not required [3]	High cost [3] Some methods have low productivity Lock on 6+ satellites required [1]
LiDAR	High productivity [1,4] Can be used during the night [3] Airborne LiDAR can survey areas that are difficult to access [3] Not affected by vegetation cover [4]	Very high cost [1] Resolution may be insufficient to measure small changes [2] Systematic errors on some terrains [3]
TLS	High accuracy [3]	Unable to capture all aspects of complex topographies (depending on equipment positioning) [3]
Total station	Low cost Accurate	Line-of-sight required [3] Low productivity [1,3] Accuracy decreases with distance from base [3]
Stereo-photogrammetry	High productivity Once set up, no operator required [2] Continuous information can be captured [3]	Low resolution [3] Equipment must be left in position for long periods of time (depending on survey) and may be vandalised or damaged Does not work in fog, mist etc [3]

Once elevation data has been collected using dGPS, it is normally viewed and processed further in GIS. At its simplest, this use of the data makes it possible to view the survey area or features on a rotatable digital map (e.g. Lo Curzio and Magliulo, 2010), and to use interpolation methods to create DTMs (e.g. Casas *et* al., 2006; Baptista *et al*., 2008). Importing dGPS data to GIS also opens up other possibilities, which include combining the current survey data with data obtained on previous surveys, or by other researchers. It is also possible to use GIS functions to measure changes in volumes or the position of features between two or more surveys of the same area/feature conducted at different times (e.g. Bertoni *et al*., 2011).

Conclusion

dGPS is a highly accurate method of directly acquiring elevation data. Considerable improvements in the capabilities of dGPS systems have been made since their first use in geomorphology in the 1990s. These improvements include technological advances which have led to more accurate and portable systems, as well as adaptations of the standard dGPS equipment to enhance productivity. dGPS is not the only method for acquiring elevation data, but it is one of the most accurate and simplest to use methods currently available. In any study where acquisition of elevation data is required, it is important to consider the most appropriate technique, as each has different advantages and disadvantages. The selection of technique will be dependent on a number of factors, including the area to be surveyed, time and finances available, and the desired balance between productivity and accuracy. However it is not necessary to consider the selection of a surveying technique as an ‘either/or’ decision. Numerous studies have shown the benefits of using two or more survey methods to provide a greater understanding of geomorphological features and processes than would have been achievable using only one method. dGPS is an excellent tool when used in isolation for mapping geological features or areas of interest, and assessing changes in position or volume. Equally, it can make a valuable contribution to studies employing other techniques, either to contribute to the collection of survey data or to ground-truth the accuracy of other methods.

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