# Application of GNSS-RTK derived topographical maps for rapid environmental monitoring: A case study of Jack Finnery Lake (Perth, Australia)

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## Abstract.

In environmental monitoring, environmental impact assessments (EIA) and environmental audits (EA), topographical maps play an essential role in providing a means by which the locations of sampling sites may be selected, in assisting with the interpretation of physical features, and in indicating the impact or potential impact on an area due to changes in the system being monitored (e.g., spatially changing features such as wetlands). GNSS (Global Navigation Satellite Systems) is hereby presented as a rapid method for monitoring spatial changes to support environmental monitoring decisions and policies. To validate the GNSS-based method, a comparison is made of results from a small-scale topographic survey using radio-based real-time kinematic GNSS (GNSS-RTK) and total station survey methods at Jack Finnery Lake, Perth, Australia. The accuracies achieved by the total station in this study were 2 cm horizontally and 6 cm vertically, whilst the GNSS-RTK also achieved an accuracy of 2 cm horizontally, but only 28 cm vertically. While the GNSS-RTK measurements were less accurate in the height component compared to those from the total station method, it is still capable of achieving accuracies sufficient for a topographic map at a scale of 1:1750 that could support environmental monitoring tasks such as identifying spatial changes in small water bodies or wetlands. The time taken to perform the survey using GNSS-RTK, however, was much shorter compared to the total station method, thereby making it quite suitable for monitoring spatial changes within an environmental context, e.g., dynamic mining activities that require rapid surveys and the regular updating of the monitored data at regular intervals.


**Keywords.** GNSS application, environmental monitoring, environmental audit, topographic maps, EIA

# 1 Introduction

Topographic maps have long been used in some form or another to define the cultural and natural features of the landscape. They require the carrying out of *topographic surveys*, whose purpose is to gather data about the natural and man-made features of an area of interest, in particular the spatial distribution of elevation, to give a three-dimensional representation of the area. Topographical maps are used for a variety of situations, including cadastre (e.g., Jacobs, 2005), engineering (e.g., US Army Corps of Engineers, 2007), earthworks (e.g., Garget, 2005), archaeology (e.g., Kvamme *et al.*, 2006), land deformation monitoring (e.g., Gili *et al.*, 2000), basic landscape and geological mapping (e.g., Reynolds *et al.*, 2005; Lavine *et al.*, 2003), and the use of such information in a digital database as a fundamental GIS (Geographic Information System) layer for environmental monitoring and management (e.g., Braun *et al.*, 2001).

The role of topographic maps in supporting environmental monitoring has been highlighted, e.g., by Hendricks (2004) who identifies the use of topographical maps as the provision of means for determining the nature of landforms, hydrology and, in some cases, the vegetation of an area. Topographic maps also find use in environmental monitoring that support environmental impact assessment (EIA) or environmental audit (EA) legislations. Most of the environmental monitoring of spatially variable features such as small water bodies required in support of EIA and EA may not require very high accuracies and as such, topographic maps with horizontal accuracies of up to 3 m could suffice (see, e.g., US Army Corps of Engineers 2007, Table 4-3b). Other environmental tasks, e.g., changes in sea level, require very accurate measurements, to within mm level. The accuracy of a topographic map being used in support of environmental monitoring will therefore depend on the purpose at hand.

In Germany, for example, deep hard-coal mining activities by the company "Deutsche Steinkohle AG" (DSK) has resulted in subsidence movements, thereby necessitating high demands on planning and monitoring since such effects might entail lasting changes and influences on the environment (Fischer and Spreckels, 1999). To minimize possible effects, extensive environmental compatibility studies were performed and detailed prognosis carried out to satisfy EIA legal requirements. In these studies, topographic maps were used to make a prognosis and to forecast the effect of mining excavations (Fischer and Spreckels, 1999). Fischer and Spreckels (1999) report on the limitations of the photogrammetry measurements and high-resolution digital terrain models (DTM) that describe the topographic situation, information on biotopes and the actual land-cover and propose a multi-temporal satellite dataset. They suggest that for environmental changes occurring over wider spatial areas (e.g., 1500 $km^2$), topographical maps generated from such multi-temporal remote sensing are advantageous compared to those from photogrammetry methods. In another example, Ji et al. (2001) show how thematic maps generated using remote sensing were useful in monitoring urban expansion, which contributes to the loss of productive farmlands in China. Similarly, Shalaby and Tateshi (2007) applied remote sensing and GIS generated maps to monitor land-cover and land-use changes in the north western coastal zone of Egypt. Their results indicate that a very pronounced land cover change has taken place as a result of tourism and development projects during the study period.

For monitoring environmental changes occurring over smaller areas (e.g., Jack Finnery Lake used in this study has an area of only 12000 $m^2$), the use of remote sensing and photogrammetry techniques to generate topographical maps is quite expensive and as such, the use of conventional methods such as total station and GNSS-generated topographical maps may be a more feasible approach. This is demonstrated, e.g., in the work of Fischer and Spreckels (1999) who demonstrate how the Global Positioning System or GPS (a GNSS system) provided results whose accuracy in height was nearly identical and within the precision of remote sensing methods, and thus could be useful in detecting mining subsidence, enabling the updating of monitoring data at regular intervals. Another example is presented in Gili *et al.*, (2000) where GNSS generated topographical maps are shown to have the capability to support environmental monitoring of the Vallcebre landslide in the Eastern Pyrenees (Spain), which had been periodically monitored using terrestrial photogrammetry and total station methods since 1987. Gili et al. (2000) found that the GNSS-RTK generated topographic maps allowed greater coverage and productivity with similar accuracies (i.e., 12 to 16 mm in the horizontal, and 18 to 24 mm in elevation) as obtained by classical surveying methods (Gili e*t al.*, 2000). Tokmakidis *et al.* (2003) produced a GNSS-generated topographic map and digital terrain model (DTM) of an area around

Kilkis, Northern Greece, for land management purposes and found the results to be comparable with existing topographical maps produced 25 years earlier that were derived using conventional photogrammetrical techniques, where differences from a few centimetres up to a meter were found.

The examples given above illustrate the major influence on topographic surveys that has resulted from the development of GNSS systems. The past decade has seen a growth in the use of these systems across many areas of the surveying industry. GPS, operated by the United States military, was the first and is still the only fully operational GNSS, although the then Soviet Union (and now Russia) operates its own GNSS called GLONASS with about 24 operating satellites. In addition, several next-generation GNSS are currently being developed by a number of nations, in particular the Galileo system of the European Union and the Chinese Beidou (Compass) system. The possibility of incorporating all the information that may be made available from such an increase in satellite coverage has the potential to deliver much greater accuracies (e.g., 1-3 m autonomous positioning level accuracy or up to mm level accuracies for relative positioning approaches), and increased reliability and availability to the spatial information industry. This will in turn support environmental monitoring tasks, most of which require accuracies no greater than cm level.

Five general classes of GNSS surveying methods are available: static baseline, rapid-static, pseudo-kinematic, radio-based real-time kinematic (RTK or GNSS-RTK, see Fig. 1), and real-time network RTK (Hoffman-Wellenhof *et al.*, 2001). The present contribution focuses on the applicability of radio-based RTK (henceforth referred to as GNSS-RTK) to small-scale topographic surveys that may be necessary for supporting environmental monitoring.

Compared to conventional methods for generating topographical maps, GNSS-RTK has the advantage of being less expensive in terms of time and labour and can provide adequate accuracies for most types of topographical surveys. These advantages are only evident, however, as long as the user has the skill and knowledge to use the system, and satellite visibility is adequate. In particular, knowledge of possible error sources is important in successfully applying GNSS-RTK.

This paper is concerned with assessing the performance of the Sokkia GNSS-RTK system and validating it using a Sokkia SET 1X Total Station system over an area covering the southwest corner of the Bentley campus of the Curtin University of Technology, Perth, Western Australia (henceforth referred to as Curtin). The performance of each system will be assessed in terms of their advantages and limitations. The results obtained are compared in terms of the accuracies achieved, the time taken and the limitations inherent in each system. The surveys carried out are intended to serve as a case study for those who need to carry out topographic surveys of an area under some form of environmental investigation, as well as monitoring features such as the changing extent of smaller water bodies. In particular, this information will be useful for users who intend to use GNSS-RTK techniques for environmental monitoring tasks.

# 2. Method

### *2.1 GNSS-RTK and topographical surveys*

The GNSS-RTK approach (Figure 1) has been applied to various types of topographic surveys, including those done for the *utilities industry, forestry and natural resources, land management, landscaping, precision farming, civil engineering, land-deformation monitoring, open pit mining, and cadastral surveying*. It is a differential positioning technique that uses the known coordinates of a reference station occupied by a base receiver to determine the horizontal coordinates of unknown points visited by a rover receiver with an accuracy of up to cm level (El-Mowafy, 2000). This involves the use of a data link that transfers measurements acquired at the reference receiver to the roving receiver to permit the calculation of the rover's coordinates at the time of a measurement (Lemmon and Gerdan, 1999). It is, however, less precise and less accurate for determining vertical heights compared to the horizontal measurements and requires that the heights be transformed to the local vertical datum, (e.g., the Australian Height Datum, AHD; Featherstone and Stewart, 2001).

The surveys described in this work were performed over a period of three days. On the first day, the GNSS-RTK survey was undertaken, followed by the total station system over the next two days. The GNSS-RTK system used was the Sokkia GSR2700 ISX (Figure 2, left) and the total amount of time taken was 7 hours. The GSR2700 ISX features a fully integrated, triple-frequency receiver where it supports GPS L2C and L5 as well as GLONASS L1 and L2 signals (Sokkia, 2009), although only the GPS L1 and L2 signals were used in this study. The system is completely cable free and can be set up and operated in base and rover modes. The manufacturer's stated accuracy when undertaking GNSS-RTK surveys is 10.0 mm ± 1.0 ppm horizontally and 20.0 mm ± 1.0 ppm for the vertical component. The total station used was the Sokkia SET 1X (Figure 2, right). The instrument reads to 1" of arc with a distance accuracy of (5 ± 2.0 ppm) x D mm in rapid mode with a prism and (2 ± 2.0 ppm) x D mm in fine mode (Sokkia, 2009 ).

**FIGURE 1**

**FIGURE 2**

### *2.2 Study area*

The topographic surveys were conducted in the south-west corner of Curtin’s Bentley campus, around Edinburgh Oval, as shown in Figure 3. The area around the oval was large enough to include various features and terrains, such as trees, buildings and roads, allowing the capabilities of each system to be comprehensively tested. A control network of pegs was setup in the survey area so as to compare horizontal and vertical measurements taken by both the GNSS-RTK and the traditional total station techniques with 'true' peg positions (Figure 2). These pegs were also used to compare vertical measurements as the 'true' heights of the pegs could be obtained using a levelling instrument, which is an independent and more accurate means of measuring heights (see, e.g., Uren and Price, 2010). Concrete pillars that form part of the Curtin GNSS Baseline Network around the site were used to provide checks (Figure 4). Distances were directly measured between the pegs using the total station system (described below) and elevations were obtained by levelling from the pillars using an automatic level. The lengths of particular features were measured with a steel tape so as to compare true lengths with those found from the resulting topographic maps produced by the two techniques.

**FIGURE 3**

**FIGURE 4**

### *2.3 Data Collection*

For the GNSS-RTK survey, a receiver was set up on pillar 18 (Figure 3, right), as the base station, based on its central location within the area of interest and open unobstructed sky view. Data was logged using an Allegro CX controller through a Bluetooth connection with the roving receiver. Coordinates for pillar 18 were obtained from Landgate (the Western Australian Government land and property information agency). The vertical heights of both receivers were also measured and entered into the controller, with the roving receiver set to be above head height at 1.8m on a pole. Once the Bluetooth connection was established between the reference station controller and the roving receiver, the system was ready for observations. On the one hand, when using GNSS, once a successful initialisation has been achieved, a roving antenna becomes a high precision coordinate generator that does not require a line-of-sight position relative to the reference station, unlike total station techniques (Roberts, 2005). However, on the other hand, its use is limited by the need for clear views of the sky and as such is significantly affected by the presence of tree cover and tall buildings which block or reflect the signals from GNSS spacecraft (i.e., multipath errors).

A 20 m grid of spot observations was taken in the open-field areas. However, the grid was altered in areas with rougher terrain in order to more accurately capture the changes in elevation. Areas containing trees were defined in the survey as opposed to picking up each individual tree, which could not be done due to the obstruction of satellite visibility. The corners of the buildings on the north side of the study area and the sides of the roads surrounding the area were all identified. Observations were made 2 m offset from the building corners as observations could not be taken directly at the buildings' corners due, again, to satellite signal obstruction as well as multipath errors (see, e.g., Hoffman-Wellenhof *et al.*, 2001). Observations were taken at the other pillars within the study area as checks and on the control pegs to allow comparisons with the total station observations.

For the total station survey, existing controls were used by setting the instrument up on the GNSS calibration pillars within the study area (Figure 3, left). Features and spot heights were found using a peanut prism screwed onto a prism pole. In order to survey the entire study area, additional survey points were established offset from the pillars for the instrument to be setup on (Figure 5). These control points had to be established to survey around the dense vegetation south of the lake and around the buildings to the north of the survey area. The coordinates of these control points were adjusted using the Bowditch method (e.g., Uren and Price, 2010) to close onto nearby pillars. The heights of each control point were established by levelling from the closest pillar.

**FIGURE 5**

### *2.4 Data Processing*

Once the observations were collected, the data from the GNSS-RTK survey was downloaded from the controller and imported into CivilCAD as a SDR33 file. Data from the total station survey was downloaded directly from the instrument to be imported into CivilCAD as a SDR2 file. Contours were created within this software using the DTM tool. The contour maps were then exported as DXF files and brought into Microstation for drafting and mapping of features. This was done because Microstation offers better drafting capabilities than CivilCAD. Coordinates were converted automatically by the Allegro software from geographic coordinates and ellipsoidal heights to Map Grid of Australia (MGA) 94 coordinates and AHD (Australian Height Datum) heights. Topographical maps provide different information, depending on the needs of the specific client or end-user, and are presented in many differing sizes and scales. Smaller-scale topographic maps generally employ scales ranging from 1:1000 to 1:10000, depending on the size of the area surveyed, with contour intervals typically ranging from 0.5 m to 1 m, naturally depending on the terrain (US Army Corps of Engineers, 2007). Fields such as engineering traditionally require greater accuracies than, for example, environmental monitoring. Hence, different approaches need to be taken when preparing maps for specific purposes, with the accuracy required such that there can be no plotable error in the survey data. For example, Hall (1994) states that "A line can be hand drawn on a sheet of paper to within 0.25 millimetres and consequently, if a survey is to be undertaken at 1:1000 scale, all measurements must be sufficiently accurate to ensure that the relative positions of any point with respect to any other point in the survey can be stated to an accuracy within 0.25 millimetres at survey scale, at 1: 2000 this represents 50 centimetres". Therefore, the field methodology followed when conducting a topographic survey will depend upon the desired final accuracy.

In this study, contour intervals of 0.25 m were selected due to the relatively flat topography of the study area at a scale of 1:1750 for an area of 174,000 m². 3D DTMs were produced from the data resulting from both surveys and were created with Surpac using the DTM creation module. A simple linear regression analysis between the two techniques for distances and vertical heights of the control pegs was evaluated using Microsoft Excel, which also provided the necessary statistics for the differences between the horizontal and vertical data obtained using both methods.

# 3 Results

## *3.1 GNSS topographic maps and validation*

The mean difference between the ground control distances and the distances interpreted from the 1:1750 topographic maps derived from both the total station and GNSS-RTK surveys were 0.061 m and 0.276 m, respectively (Table 1). Distances on the maps could be read to the nearest 0.5 mm, corresponding to a reading error of 0.875 m. Therefore, the variation of the distances measured on the topographic maps from both techniques can be viewed as being insignificant at a scale of 1:1750. The standard deviation of the differences between the topographic map distances and the control was 0.105 m and 0.369 m for the total station and GNSS-RTK, respectively (Table 1). Both techniques had similar horizontal accuracies, however, the precision was significantly higher for the total station compared with that from the GNSS-RTK. Likewise, the variability in distances determined by GNSS-RTK is quite large compared to that from the total station, the largest differences occurring where observations were taken at pegs 3 and 5 (Table 1). This is also highlighted in Figure 6 where the peg lines that involve pegs 3 and 5, namely peg lines 2, 3, 6, 9, 11, and 13, show the greatest differences between methods. The reason for this is the proximity of a large, densely forested area near these pegs which would have reduced satellite visibility and introduced multipath errors.

**TABLE 1**

**FIGURE 6**

A linear regression analysis of the distances between the control pegs as measured from the GNSS-RTK and total station topographical maps gave $R^2$ values (the fraction of the variance in the total station or GNSS-RTK measurements that is accounted for by a linear fit of the control measurements to the total station or GNSS-RTK measurements) equal to 1, with the intercepts of 0.002 m and 0.124 m for the control vs. total station and control vs. GNSS-RTK plots, respectively, and slopes within 0.0003 and 0.003 units of 1 for the control vs. total station and control vs. GNSS-RTK plots, respectively (Figure 7). This suggests that there is more variability in the GNSS-RTK horizontal measurements compared with the total station values. However, there could also be a bias in the total station vs. control regression analysis arising from the fact that the same instrument was used to measure the horizontal distances for the total station survey and the control survey. This could result in a closer correlation between the two data sets compared with the case where different instruments were used for each survey. The distances from each topographic map are examined further in Figure 8, which shows that the distances measured from each map are strongly correlated, with $R^2 = 1$. This suggests that the GNSS-RTK technique produces a product of equal quality to the total station technique for topographic mapping purposes, at least at this scale of mapping and survey (i.e., 1:1750).

**FIGURE 7**

**FIGURE 8**

Figures 9 and 10 show the topographic maps produced from each method. The only major visible discrepancy between the two maps is the representation of the trees, again because the GNSS-RTK was unable to take observations under the dense tree cover and the occurrence of multipath effects. Hence, as with the buildings, observations had to be taken a few meters from the actual position of the trees. In addition, trees in the middle of the cluster could not be picked up at all due to a lack of satellite visibility.

Table 2 lists lengths of particular features as measured by a steel tape and compares them to the equivalent lengths inferred from the topographic maps. The mean errors are 0.2 m for total station and 0.5 m for GNSS-RTK, which better than the accuracy range of 1.6 m to 3 m generally required for a map of this scale (see US Army Corps of Engineers, 2007, Table 4-3b). These results therefore highlight the fact that the GNSS-RTK technique generally achieved accuracies suitable for this topographic map scale of 1:1750. The largest differences are found when measuring the faces of buildings, due to the fact (discussed earlier) that the GNSS-RTK receivers cannot be directly positioned on the building corner, as opposed to a total station prism, due to multipath errors and diminished satellite signals.

However, the building was still positioned on the GNSS-RTK 1:1750 topographic map (Figure 10) with sufficient accuracy, with the difference in the lengths measured by the two techniques of the sports pavilion wall (ID 9, Table 2) being 1.75 m, corresponding to a 1 mm difference on the topographic maps.

**FIGURE 9**

**FIGURE 10**

**TABLE 2**

### *3.2 3D Elevation Model Comparison*

The 3D elevation models produced in Surpac for each of the survey techniques show similarities for most of the study area. Discrepancies, however, arise in the areas around the lake, especially on the north-east shoreline highlighted by the yellow box in Figures 11 and 12, where there is dense tree cover. Few observations could be taken using the GNSS-RTK due to inadequate satellite visibility, and so a less accurate depiction of the terrain in this area was modelled. However, in areas where satellite visibility was adequate, both techniques produced similar results and GNSS-RTK achieved a suitable accuracy for the visual representation of the study area's terrain.

**FIGURE 11**

**FIGURE 12**

### *3.3 Application to Jack Finnery Lake*

The area of Jack Finnery Lake was determined from the GNSS-RTK survey results and compared with areas found from Google Earth Pro imagery for the years 2000, 2005, and 2009 (Figure 13). It should be pointed out that the Google maps used in this study are not so accurate and are thus not suitable for high-precision quantitative analysis. However, for the purpose of validating the changing trend of the lake's size as done in this work, they are adequate. The areas of the lake from the Google maps were determined using the Ruler tool by drawing a polygon around the lake's perimeter, from which an area is automatically calculated and displayed. The trend shown by the Google images suggest that the lake is gradually shrinking over time, as indicated by the decreasing lake area from the years 2000 to 2008 (Figure 14). The data obtained from the GNSS-RTK in 2009 (Figure 13 bottom-right) follows this trend with a smaller area compared to 2008 (Figure 13 bottom left). This shows that the GNSS-RTK technique can be used for surveys needed for environmental applications, such as wetland management or the monitoring of the size of specific features, provided there is adequate satellite coverage. Therefore, instead of using expensive satellite imagery to monitor smaller water bodies over time, GNSS-RTK can be used to map waterlines quickly and accurately to monitor the growth or recession of water bodies (or other features, e.g., extent of erosion or different vegetation) over time.

**FIGURE 13**

**FIGURE 14**

## 4. Discussion and conclusion

Attributes that are important to topographic maps can be successfully identified and represented by both the Sokkia total station and Sokkia GNSS-RTK techniques. The GNSS-RTK measurements were found to be less accurate and precise than those from the total station method, especially for vertical measurements. This was expected due to the error sources encountered with GNSS-RTK that are not experienced with total station methods, the most significant being from multipath errors caused by surrounding features. However, the GNSS-RTK technique was capable of achieving a level of accuracy sufficient to develop a reliable topographic map at a scale of 1:1750 which suffices for most environmental monitoring purposes. At this scale, given that the GNSS-RTK generated topographical map achieved a horizontal accuracy of 2 cm and a vertical accuracy of 28 cm, it would be useful for most types of environmental monitoring, except where heights need to be more accurate than 28 cm, such as land subsidence monitoring. We point out here, however, that this accuracy is not the absolute achievable value, since GNSS-RTK accuracy depends on many factors, which include satellite availability and visibility, signal blockage from trees and buildings, the effects of multipath error, and the experience of the observers, to just list a few. These error sources could have contributed to the accuracy we achieved. The results, however, indicate the potential of GNSS-RTK to generate topographical maps capable of supporting the environmental applications listed in Table 3, although we must point out that this is not conclusive given the problems of error sources and limited data.

**TABLE 3**

The time taken to perform the survey was much shorter using the GNSS-RTK compared with the total station method, where the need for multiple setups and a traverse to establish control on the multiple stations greatly increased the time taken to perform the survey. Therefore, GNSS-RTK would be the recommended method for performing surveys where there is a need for the rapid generation of topographic maps that could support the monitoring of environmental features, as demonstrated in the case of Jack Finnery

Lake. However, the total station method would become the preferred one for areas with dense tree cover and other obstructions that would block satellite visibility and introduce significant multipath errors.

The accuracies achieved by each survey technique were compared against typical accuracies desired for particular survey tasks. It was found that the GNSS-RTK method did not meet the required accuracies for cadastral work, utility surveys, land deformation surveys, or archaeological surveys that require cm-mm level accuracies, but is sufficient for environmental monitoring which does not require such high accuracies, such as the mapping of waste disposal areas. Therefore, for environmental monitoring of areas with adequate satellite visibility throughout the survey area and fewer obstructions introducing multipath error, the generation of topographic surveys that serve as a preliminary reconnaissance for environmental studies, or to quickly examine the changing spatial dimensions of a feature, such as a small water body during an environmental audit, GNSS-RTK is recommended.

Environmentalists can achieve cm levels of accuracy and instantaneous results in the field using GNSS-RTK, which requires observation times of only a few seconds at each surveyed point. Compared with conventional equipment and techniques, GNSS-RTK can dramatically decrease the time and manpower needed to complete an environmental monitoring survey of spatial changes at localized levels and which require constant updating of the monitoring data at regular intervals.

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## References


Braun, J., Simões, C., Vogt, S., Bremer, U.F., Blindow, N., Pfender, M., Saurer, H., Aquino, F. and Ferron, F.A. (2001) An improved topographic database for King George Island: compilation, application and outlook, Antarctic Science, vol. 13, no. 1, pp. 41-52.

El-Mowafy, A. (2000) Performance Analysis of the RTK Technique in an Urban Environment, *The Australian Surveyor*, vol. 45, no.1, pp. 47 – 54.

Featherstone, W.E. and Stewart, M.P. (2001) Combined Analysis of Real Time Kinematic GPS and its Users for Height Determination, *Journal of Surveying Engineering*, vol. 127, no. 2, pp. 31-51.

Fischer C, Spreckels V (1999) Environmental Monitoring of Coal Mining Subsidences by Airborne High Resolution Scanner. IEEE, 0-7803-5207-6/99 pp. 897-899.

Garget, D. (2005) Testing of Robotic Total Station for Dynamic Tracking. University of Southern Queensland. http://eprints.usq.edu.au/

Gili, J.A., Corominas, J. and Rius, J. (2000) Using Global Positioning Techniques in Landslide Monitoring, *Engineering Geology*, vol. 155, no. 3, pp. 167-192.

Hall, B. (1994) Environmental Mapping Systems – Locationally Linked Databases. Riversinfo. Precision Info. http://www.precisioninfo.com/rivers_org/au/archive/?doc_id=1

Hendricks, D.M. (2004) Maps in environmental monitoring, in Environmental monitoring and characterization, Eds. Artiola, J.F., Pepper, I.L. and Brusseau, ML., Elsevier Academic Press, California, USA, 410 pp.

Hoffman-Wellenhof, B., Lichtenegger, H. and Collins, J. (2001) Global Positioning System: Theory and Practice, 5$^{th}$ edition, Springer, Wien, New York, 382 pp.

Jacobs, P.G. (2005) Assessing GNSS-RTK for a Suburban Survey Practice, University of Southern Queensland, Faculty of Engineering and Surveying, http://eprints.usq.edu.au/546/1/PeterJACOBS-2005.pdf.

Ji, C. Y. , Liu, Qinhuo , Sun, Danfeng , Wang, Sheng , Lin, Pei and Li, Xiaowen(2001) 'Monitoring urban expansion with remote sensing in China', International Journal of Remote Sensing, 22(8): 1441-1455. DOI: 10.1080/01431160117207

Kvamme, K., Ernenwein, E. and Markussen, C. (2006) Robotic Total Station for Microtopographic Mapping: an Example from the Northern Great Plains. *Archaeological Prospection*, vol. 13, pp. 91-102.

Lavine, A., Gardner, J. and Reneau, S. (2003) Total station geologic mapping: an innovative approach to annalyzing surface-faulting hazards, *Engineering Geology*, vol. 70, pp. 71-91.

Lemmon, T. and Gerdan, G. (1999) The Influence of the Number of Satellites on the Accuracy of GNSS-RTK Positions, *The Australian Surveyor*, vol. 44, no.1, pp. 64-70.

Piras, M., Roggero, M. and Fantino, M. (2007) Monitoring of Deformation Using GNSS. *AOGS*, vol. 13, pp. 87-104.

Reynolds, W., Young, F. and Gibbings P. (2005) A Comparison of Methods for Mapping Golf Greens, *Spatial Science Queensland*, vol. 4, pp. 33-36.

Roberts, C. (2005) GPS for Cadastral Surveying – Practical Considerations. Spatial Sciences Institute, September 2005, Melbourne.

Roberts G., Meng X., Taha A., Montillet J. P. (2006) The Location and Positioning of Buried Pipes and Cables in Built Up Areas. *TS 38 - Engineering Surveys for Construction Works I*, XXIII FIG Congress, Munich. pp. 1-9.

Schmidt, J.P., Taylor, R.K. and Gehl, R.J. (2003) Developing Topographic Maps Using a Sub-Meter Accuracy Global Positioning Receiver, *Applied Engineering in Agriculture*, vol 19, no. 3, pp. 291-300.

Shalaby A, Tateishi R (2007) Remote sensing and GIS for mapping and monitoring land cover and land-use changes in the Northwestern coastal zone of Egypt. Applied Geography 27: 28-41. DOI:10.1016/j.apgeog.2006.09.004

Sokkia (2009) *GSR2700 ISX Specifications*, POINT Inc. Sokkia, USA.

Tokmakidis, K., Spatalas, S. and Pikridas, C. (2003) A Comparison of a Digital Terrain Model Obtained from GPS and Classical Data, *Proceedings of International Symposium on Modern Technologies, Education and Professional Practice in the Globalizing World*, November, Sofia, Bulgaria, pp. 30-35.

US Army Corps of Engineers (2007) Control and Topographic Surveying, *Engineering and Design Manual*, EM 1110-1-1005.

Uren, J. and Price, W.F. (2010) Surveying for engineering, 5th edition, Palgrave MacMillan, New York, 824 pp.

**TABLES:**

**Table 1:** Comparison of distances measured between the control pegs (Figure 2) on the ground and those interpreted from the 1:1750 A3 topographic maps produced from the total station (TS) and GNSS-RTK surveys.

| Peg line | Peg IDs | Control (m) | TS 1:1750 map (m) | GNSS-RTK 1:1750 map (m) | TS Error (m) | GNSS-RTK Error (m) |
|---|---|---|---|---|---|---|
| 1 | 1 - 2 | 63.001 | 63.0 | 63.0 | -0.001 | -0.001 |
| 2 | 1 - 3 | 134.312 | 134.4 | 135.1 | 0.088 | 0.788 |
| 3 | 1 - 5 | 325.423 | 325.5 | 326.2 | 0.077 | 0.777 |
| 4 | 1 - 4 | 170.151 | 170.1 | 170.1 | -0.051 | -0.051 |
| 5 | 1 - 6 | 302.144 | 302.4 | 302.4 | 0.256 | 0.256 |
| 6 | 2 - 3 | 73.200 | 73.5 | 72.8 | 0.300 | -0.400 |
| 7 | 2 - 6 | 271.078 | 270.9 | 270.9 | -0.178 | -0.178 |
| 8 | 2 - 4 | 113.359 | 113.4 | 113.4 | 0.041 | 0.041 |
| 9 | 3 - 6 | 227.435 | 227.5 | 228.2 | 0.065 | 0.765 |
| 10 | 3 - 4 | 44.925 | 44.8 | 44.8 | -0.125 | -0.125 |
| 11 | 4 - 5 | 167.168 | 167.3 | 168 | 0.132 | 0.832 |
| 12 | 4 - 6 | 188.457 | 188.3 | 188.3 | -0.157 | -0.157 |
| 13 | 5 - 6 | 264.257 | 264.6 | 265.3 | 0.343 | 1.043 |
| | | | | **mean** | **0.061** | **0.276** |
| | | | | **stan. dev.** | **0.105** | **0.369** |

**Table 2:** Comparison of feature lengths measured on the ground and their corresponding lengths as represented on a 1:1750 scale map.

| ID | Features | STEEL TAPE length(m) | TS 1:1750 map length (m) | RTK 1:1750 map length(m) | TS Error (m) | RTK Error (m) |
|---|---|---|---|---|---|---|
| 1 | North soccer goals | 7.4 | 7.00 | 7.00 | 0.4 | 0.4 |
| 2 | South soccer goals | 7.4 | 7.00 | 7.00 | 0.4 | 0.4 |
| 3 | Car park signs | 9.11 | 8.75 | 8.75 | 0.36 | 0.36 |
| 4 | pitch access gate | 8.08 | 8.75 | 8.75 | -0.67 | -0.67 |
| 5 | timber posts | 2.04 | 1.75 | 1.75 | 0.29 | 0.29 |
| 6 | Lamp posts 1 | 12.52 | 12.25 | 12.25 | 0.27 | 0.27 |
| 7 | Lamp posts 2 | 27.37 | 26.25 | 26.25 | 1.12 | 1.12 |
| 8 | Lamp posts 3 | 31.37 | 31.50 | 31.50 | -0.13 | -0.13 |
| 9 | Sports pavilion | 29.43 | 29.75 | 28.00 | -0.32 | 1.43 |
| 10 | Brick path width | 2.16 | 1.75 | 1.75 | 0.41 | 0.41 |
| 11 | Events centre | 69.72 | 70.00 | 68.25 | -0.28 | 1.47 |
| 12 | Soccer pitch | 100.37 | 99.75 | 99.75 | 0.62 | 0.62 |
| | | | | **mean** | **0.206** | **0.498** |
| | | | | **stan. dev.** | **0.482** | **0.612** |

**Table 3:** Listing of various applications of topographical maps and the generally required accuracies, and whether or not the total station or GNSS-RTK methods are suitable.

| **Type of Survey** | **Horizontal accuracy (m)** | **Vertical accuracy (m)** | **Total Station suitable** | **GNSS-RTK suitable** |
|---|---|---|---|---|
| Cadastral (Jacobs, 2005) | 0.007 | 0.035 | Yes | **No** |
| Engineering Site Plans (US Army Engineers, 2007) | 0.015 | 0.035 | Yes | Yes |
| Utilities (Roberts, 2006) | 0.015 | 0.015 | Yes | **No** |
| Land Deformation (Gili, 2000) | 0.016 | 0.024 | Yes | **No** |
| Archaeological (Kvamme et al, 2002) | 0.020 | 0.020 | Yes | **No** |
| Geological (Lavine et al, 2002) | 0.030 | 0.050 | Yes | Yes |
| Landscaping (Reynolds, 2005) | 0.050 | 0.050 | Yes | Yes |
| Agricultural (Schmidt, 2002) | 0.500 | 0.500 | Yes | Yes |
| Detail Topographic (US Army Engineers, 2007) | 0.300 | 0.600 | Yes | Yes |
| Reconnaissance Topographic (US Army Engineers, 2007) | 1.000 | 1.500 | Yes | Yes |

## FIGURES:

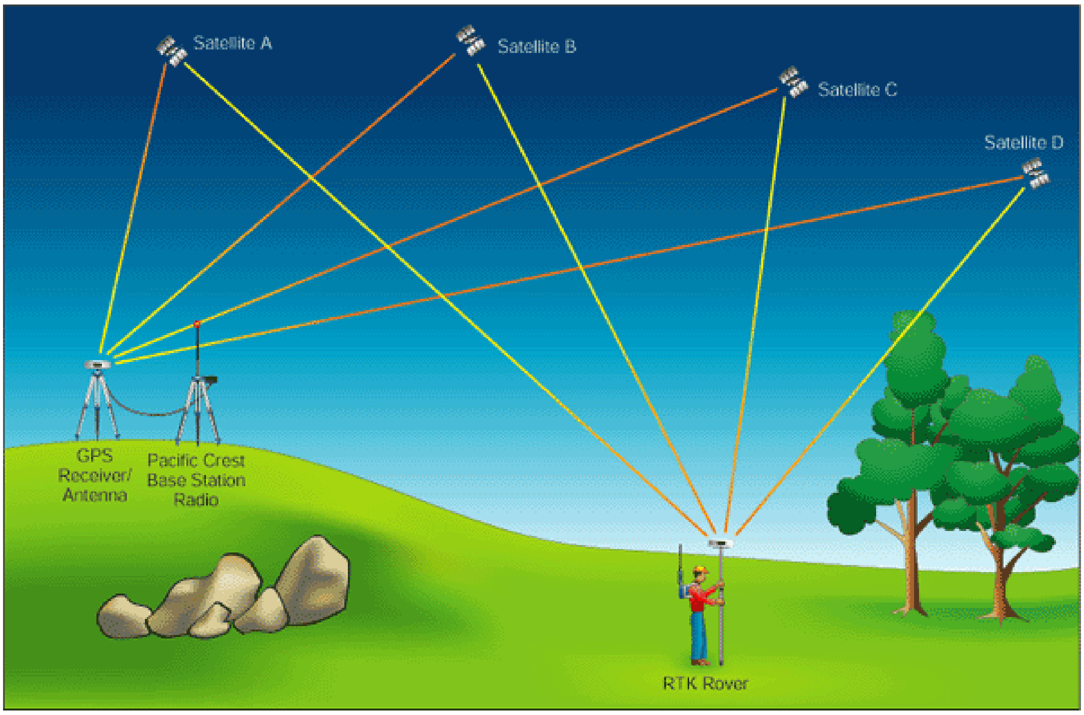



**Figure 1:** Real Time Kinematic (RTK) GNSS (El-Mowafy, 2000).

**Figure 2:** Left: The Sokkia GSR2700 ISX RTK roving receiver with attached controller (Sokkia, 2009; http://photos.instrumentsolutionsource.com). Right: Sokkia SET 1X Total Station (http://www.gisiberica.com).


**Figure 3:** The Curtin study area with the control peg network. The distances between pegs are listed in Table 1 (http://maps.google.com/maps).

Survey Area Boundary

Control Peg

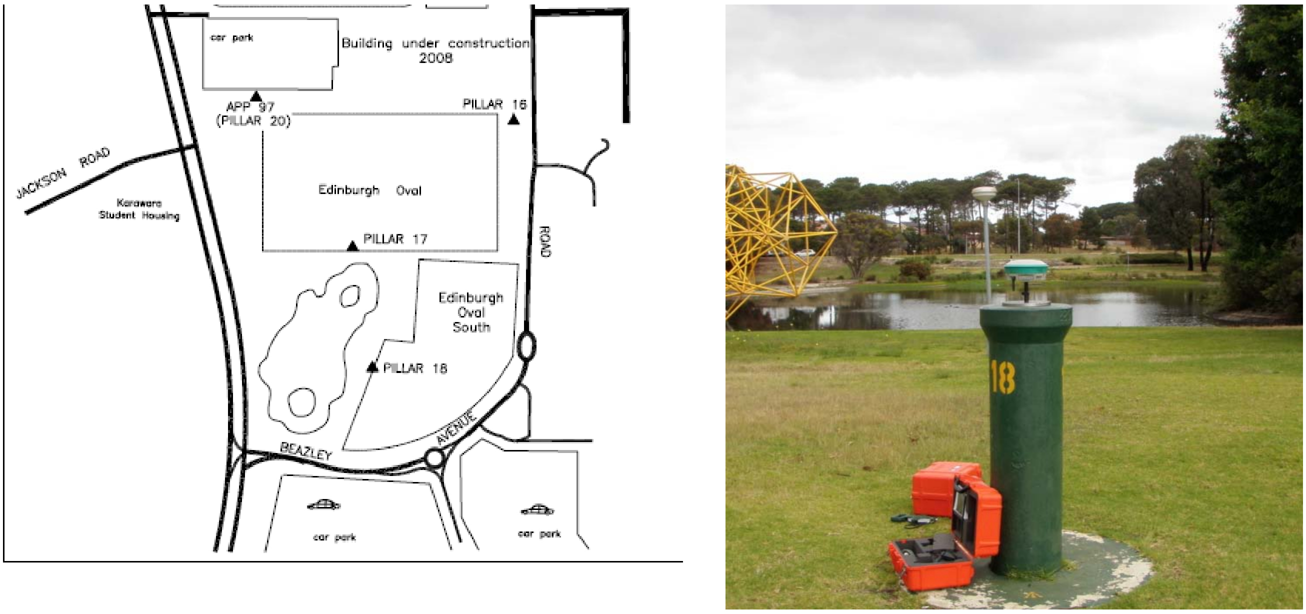



**Figure 4:** Left: The Curtin GNSS Baseline Network Pillar locations within the study area. Right: Base receiver setup on Pillar 18.


**Figure 5:** Points on which the total station was setup.

pillars,

control points established from pillars.

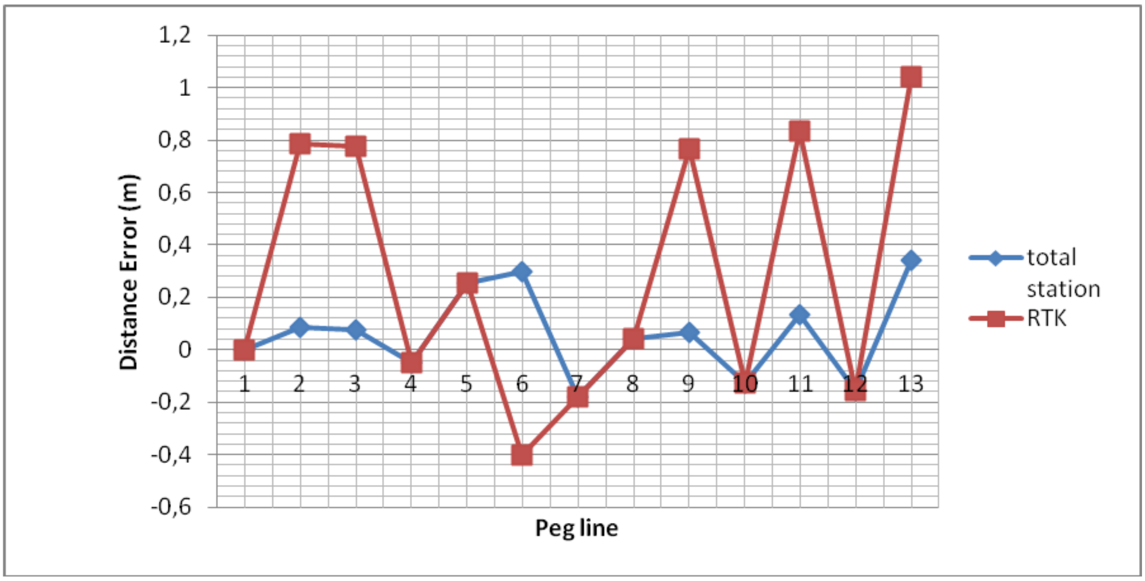



**Figure 6:** Error distribution for the distances between the control pegs as interpreted from the topographic maps produced by the total station and GNSS-RTK techniques when compared with measured ground control distances (see Figure 2 and Table 1).

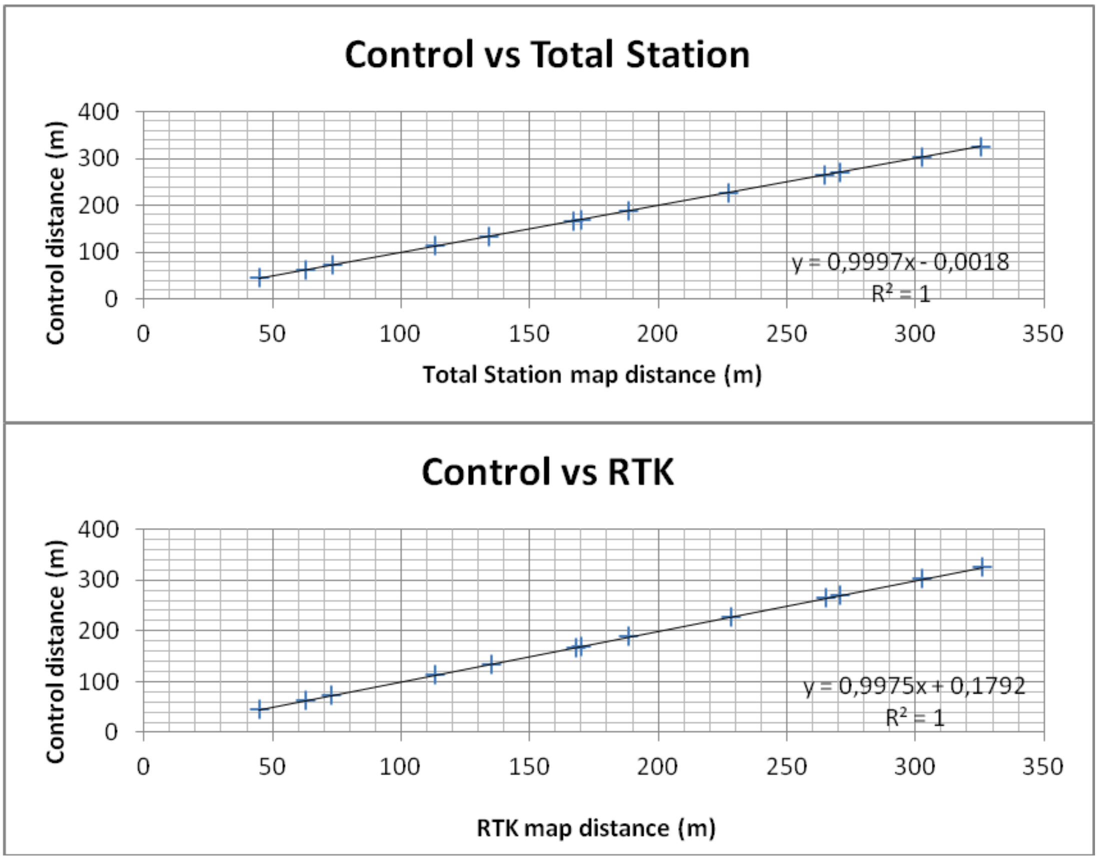



**Figure 7:** Regression analysis of distances measured between control pegs on the ground and distances interpreted from 1:1750 A3 topographic maps produced from (top) the total station and (bottom) GNSS-RTK surveys.

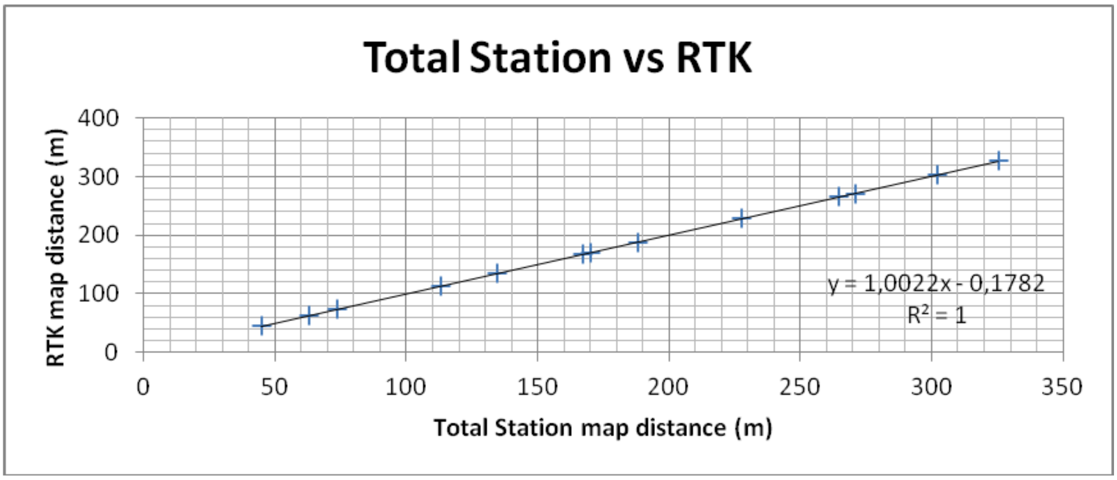



**Figure 8:** Regression analysis of distances interpreted from 1:1750 A3 topographic maps produced from the total station and GNSS-RTK surveys.

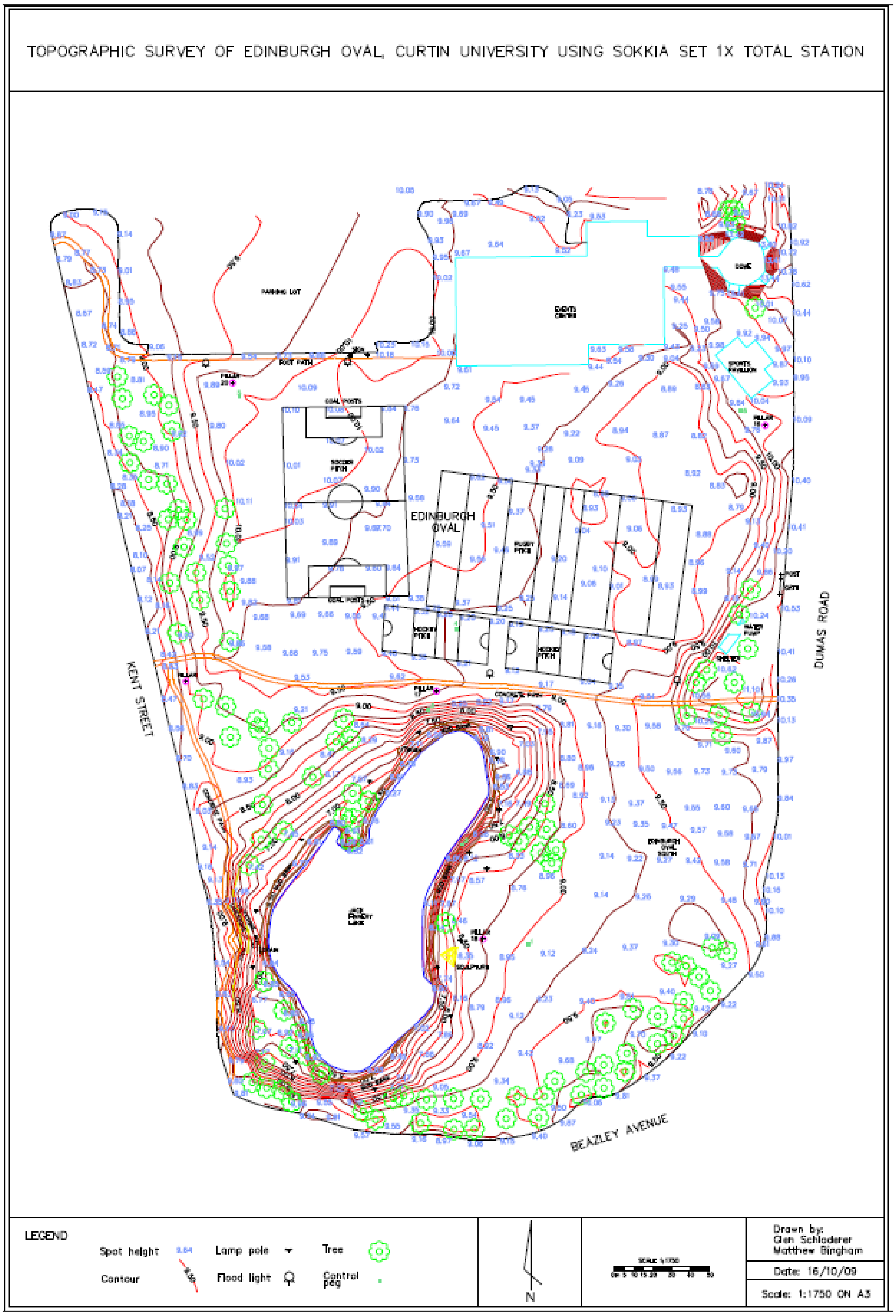



**Figure 9:** Topographic map generated from the total station survey.

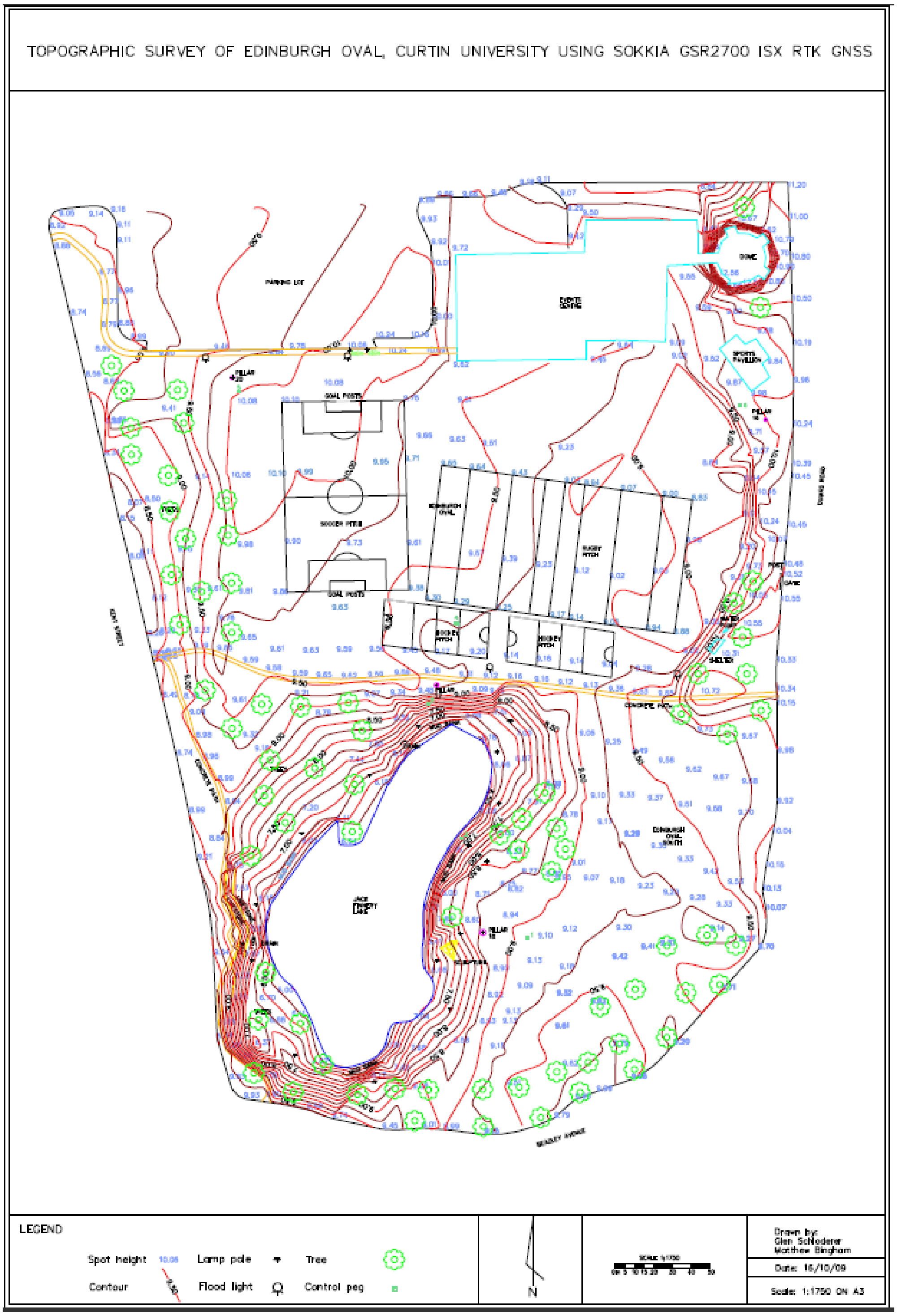



**Figure 10:** Topographic map generated from the GNSS-RTK survey.

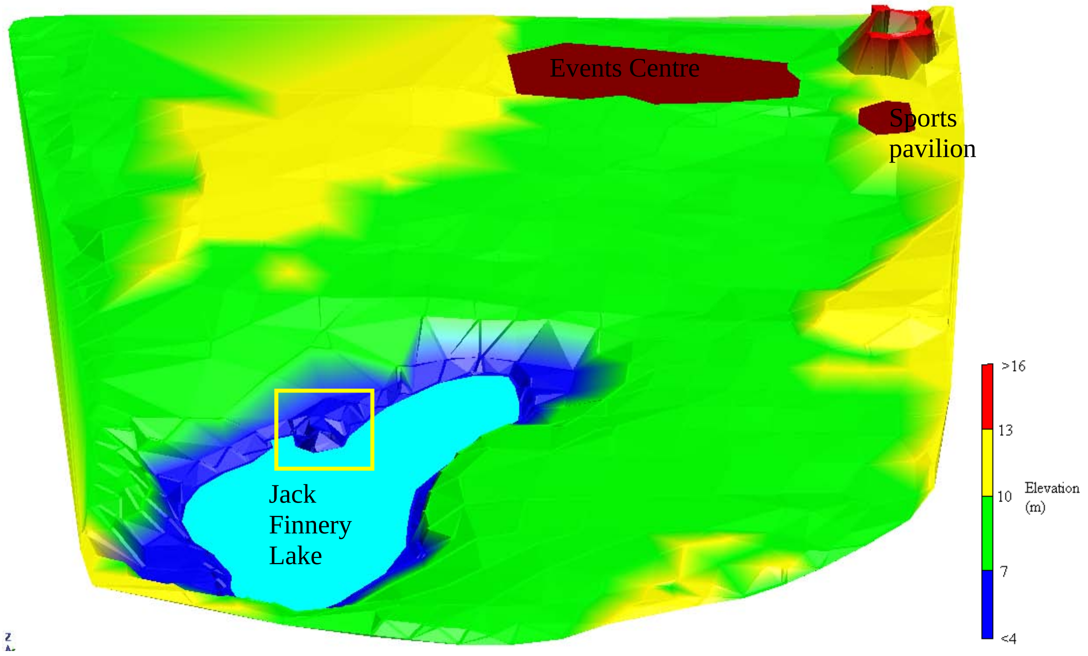



**Figure 11:** 3D elevation model produced from the total station survey.

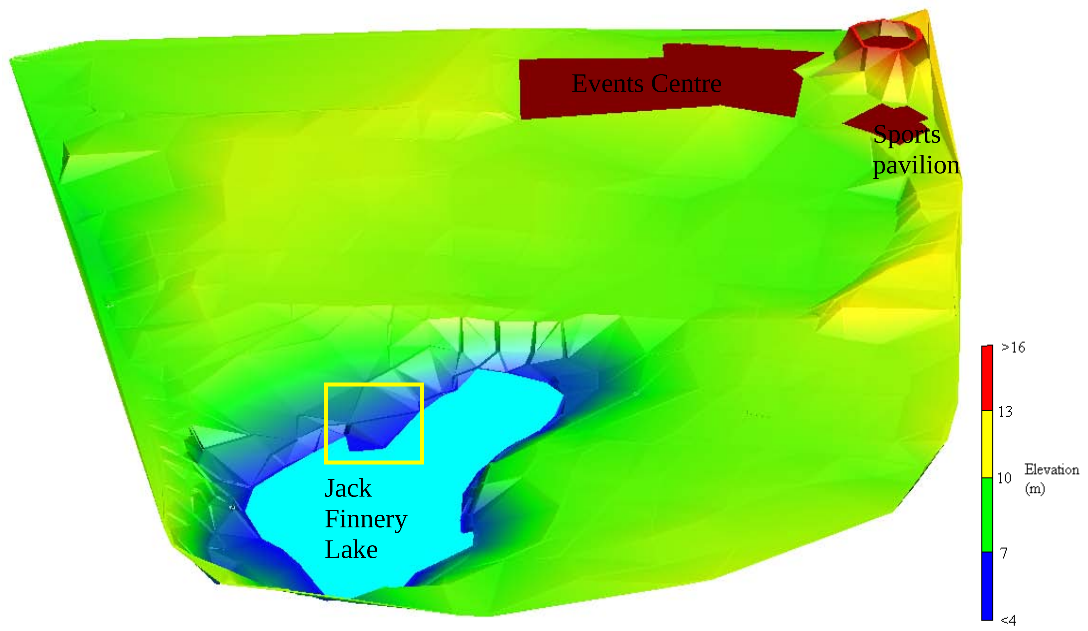
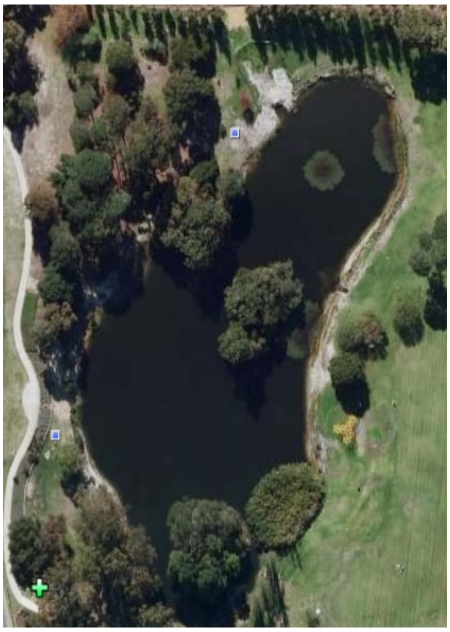


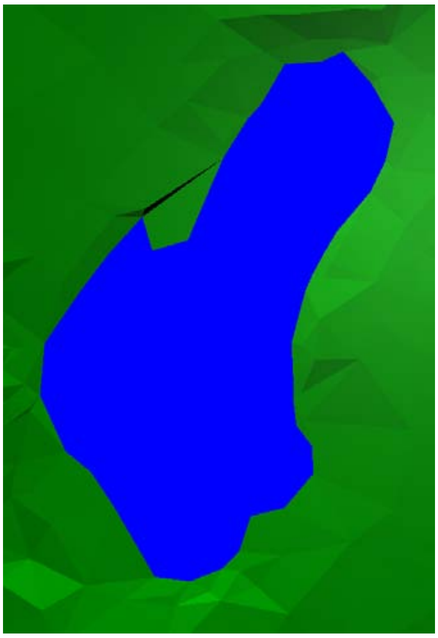

**Figure 12:** 3D elevation model produced from the GNSS-RTK survey.

Sept 2000 Area = 12300 $m^2$

Aug 2005 Area = 11922 $m^2$



May 2008 Area = 10959 $m^2$



Sept 2009 Area = 10689 $m^2$

**Figure 13:** Comparison of the area of Jack Finnery Lake during the years 2000, 2005, and 2008 as measured from Google Earth satellite imagery, and from the RTK generated model (September 2009). Satellite images obtained from Google Earth Pro.

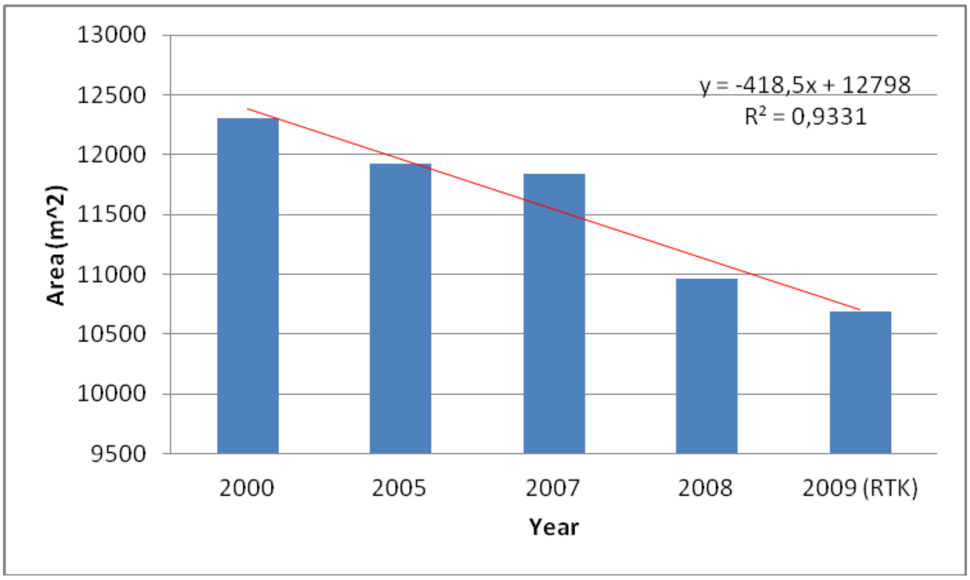



**Figure 14:** Variation of the area of Lake Finnery over time. The areas for the years 2000, 2005, 2007 and 2008 were found from Google imagery (Figure 13).