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Single-Receiver Static GNSS Surveys Using Virtual Reference Stations

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ABSTRACT

Datum control surveys are the means by which a survey control network is defined, propagated and maintained. These are performed using a combination of terrestrial survey methods, i.e. traversing and levelling, and also space-based techniques such as Global Satellite Navigation System (GNSS) surveys. For large-scale and high-quality control surveys, static GNSS has become the standard, providing high precision over long distances and connected observations, allowing for implementation of strong geometrical arrangements and giving high redundancy. For smaller projects, however, static GNSS surveys are a resource and time intensive method, with at least two receivers required, often implemented by at least two field parties, and using observation lengths upward of 10 minutes. While having the ability to provide quick measurements and limiting demand on resources, rapid GNSS positioning methods, such as Real-Time Kinematic (RTK) and Network RTK (NTRK), are insufficient for higher-class datum control surveys due to their radiations or point-based positional solutions and lack of direct connection between observations. This paper introduces an alternative method of control survey that implements elements of NRTK methodology and infrastructure, in particular the Virtual Reference Station (VRS) method, which allows a static GNSS control survey to be carried out by a single surveyor using a single receiver. Manually generated VRSs are used to link temporally separated GNSS observations by post-processed static baselines. This method is compared to a static GNSS survey, with both surveys using similar geometry. The introduced method shows encouraging results, achieving a horizontal class B and showing good agreement with the static GNSS survey (horizontal Root Mean Square coordinate difference of 17 mm) while providing an advantage in terms of resource requirements.

KEYWORDS: *Control survey, GNSS, VRS, NRTK.*

1 INTRODUCTION

The coordination and propagation of the NSW survey control network has increasingly, over the last 20 years, been performed using static Global Navigation Satellite System (GNSS) measurements, which have largely replaced terrestrial observations. Terrestrial methods, such as traversing and levelling, while providing excellent relative accuracy in the micro-survey environment (i.e. with measurement lengths of around 100 m or less), can be a time-consuming, labour-intensive and therefore costly process in control surveys spanning large areas. Furthermore, the propagation of errors means that over long distances, terrestrial methods cannot match the relative uncertainty achievable using high-precision static GNSS baselines (DFSI Spatial Services, 2012).

The transition from using terrestrial methods to using space-based technology for datum control surveys is therefore an example of technological advancement leading to an improvement in efficiency and productivity, while providing the ability to create a more homogenous and reliable survey control network at a state-wide level. This paper explores a technique that utilises further advancements in GNSS technology and, for some purposes, may provide a boost to productivity in the performance of static GNSS control surveys, and in particular in the reduction of resources required to do so.

Static GNSS classically involves simultaneous GNSS observations between two or more receivers (Dawidowicz and Kzran, 2014), often operated by two or more field parties, meaning that static GNSS can be a resource-intensive process. The method presented in this paper allows a single surveyor to perform a static GNSS survey with a single GNSS receiver. This is made possible by linking temporally and spatially separated raw GNSS observations together by computing baselines between the measured stations and a manually generated Virtual Reference Station (VRS) between them.

In order to test this technique, a traditional static GNSS survey was implemented, and the survey was then repeated using the proposed method utilising similar survey geometry for comparison. Positional and statistical results were compared along with a consideration of resource requirements for each survey.

2 TECHNICAL BACKGROUND

The process of Network Real-Time Kinematic (NRTK) positioning can produce a VRS. There are several different NRTK architectures, which have been summarised by Cina et al. (2015) into three main categories:

- Virtual Reference Station (VRS).
- Multi-Reference Station (MRS).
- Master-Auxiliary Concept (MAC).

These differing methods have been shown to have similar levels of accuracy (Janssen, 2009), albeit with slight differences with respect to some other parameters, such as the distribution of processing load and required bandwidth, which are not a focus of this study. In this paper, we utilise the methodology and infrastructure of the VRS method.

Landau et al. (2002) describe the process of the VRS method of NRTK as follows. Upon starting the GNSS receiver, a communications link is established between it and the GNSS network control centre via radio, wireless internet or the mobile phone network. Approximate coordinates of the receiver are sent to the control centre in National Marine Electronics Association (NMEA) data format. The control centre then passes on correction data in Radio Technical Commission for Maritime Services (RTCM) format (or similar) to the receiver, allowing it to compute a more accurate differential GNSS position. Finally, the control centre simulates a new, invisible and unoccupied VRS near the rover, allowing for continual computation of a differential position by the rover with corrections sent in real time. The control centre can also supply Receiver Independent Exchange (RINEX) data emanating from this VRS for post-processing. The VRS remains in place until the rover moves approximately 5 km from its initial position, causing a new VRS to be generated. This process is illustrated in Figure 1.

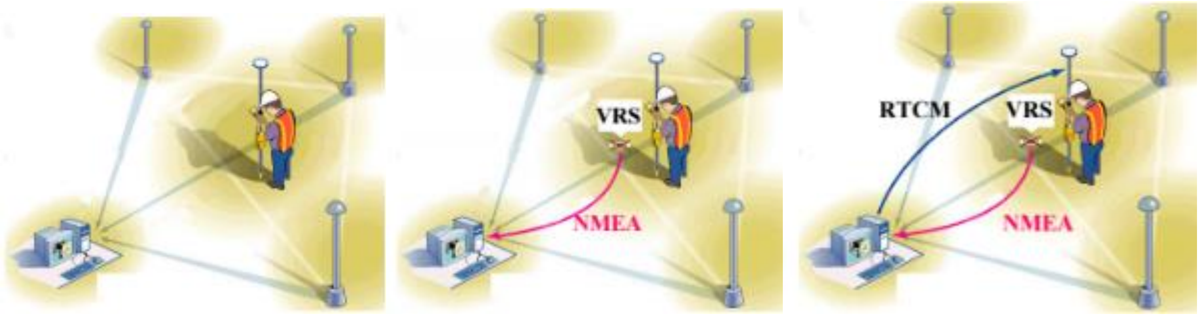

Figure 1: The process of generating a VRS (Landau et al., 2002).

Traditionally, a VRS is automatically generated and positioned in real time, allowing for a radiation to be computed by NRTK positioning. However, a VRS can also be manually generated and positioned in post-processing, and in NSW this functionality is available through CORSnet-NSW (Janssen et al., 2016; DFSI Spatial Services, 2019). The possibility therefore exists to manually compute a static baseline between raw data collected from a receiver to a strategically placed VRS that was not directly observed. Expanding on this idea, if a single surveyor with a single receiver were to collect raw GNSS data at two different survey marks and at different times, a direct connection could be made between these marks if static baselines are computed from each mark to a VRS placed in between them, providing the VRS duration spans for both observations. This principle can be applied to allow a single surveyor with a single GNSS receiver to produce a static GNSS control survey.

This technique also introduces another benefit of NRTK methodology, which may assist in difficult observing conditions. When obstacles are blocking the skyview in different directions at each receiver while using traditional static GNSS measurements, each receiver may be reading to a different subset of satellites and this may make ambiguity resolution difficult to achieve. Given that the production of a VRS will, in theory, provide an uninterrupted and complete dataset on at least one end of each baseline, the ability to achieve ambiguity resolution should become more likely and be achieved more quickly. The measurement times required could therefore be reduced. In this paper, the minimum time required for GNSS baselines in cadastral work stipulated by Surveyor General’s Direction No. 9 (SG9) (DFSI Spatial Services, 2014) of 10 minutes is adopted, regardless of baseline length.

3 NETWORK DESIGN

The area selected to implement this procedure is a 31 km^2 region in Sackville North, NSW. Throughout the area a GNSS network of horizontal and vertical class and order B2 exists, as well as two levelled marks, with vertical class and order LAL1, and these marks serve as control for the survey adjustment. Nine marks within the area were adjusted horizontally, with seven of them also being adjusted in height. For more information on the classification of class and order, the reader is referred to ICSM (2007).

A static GNSS survey was designed with a minimum density of 600 m, with the network connected in triangular or quadrilateral loops. The network was braced to four marks external to the network, one with horizontal class and order A1, and three B2 marks. These four marks also provided Australian Height Datum (AHD) control with class and order B2, as well as two marks internal to the network, with vertical class and order LAL1. The network design for the static survey is shown in Figure 2.

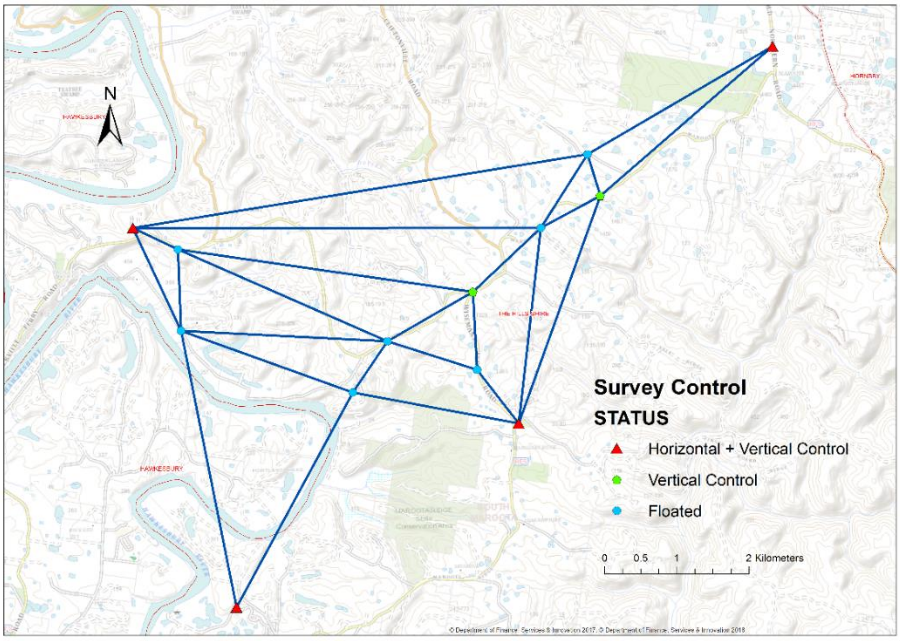

Figure 2: Static network design with survey control configuration.

This survey design was then emulated, this time using the VRS method. Each connection between marks remained consistent between surveys, but in this case marks were linked via a VRS. This design is pictured in Figure 3. VRS were placed roughly at the planimetric midpoint between marks, and the height of each VRS was set to a nominal Geodetic Reference System 1980 (GRS80) ellipsoidal height of 180 m, as this height is roughly the mean height of all stations within the network.

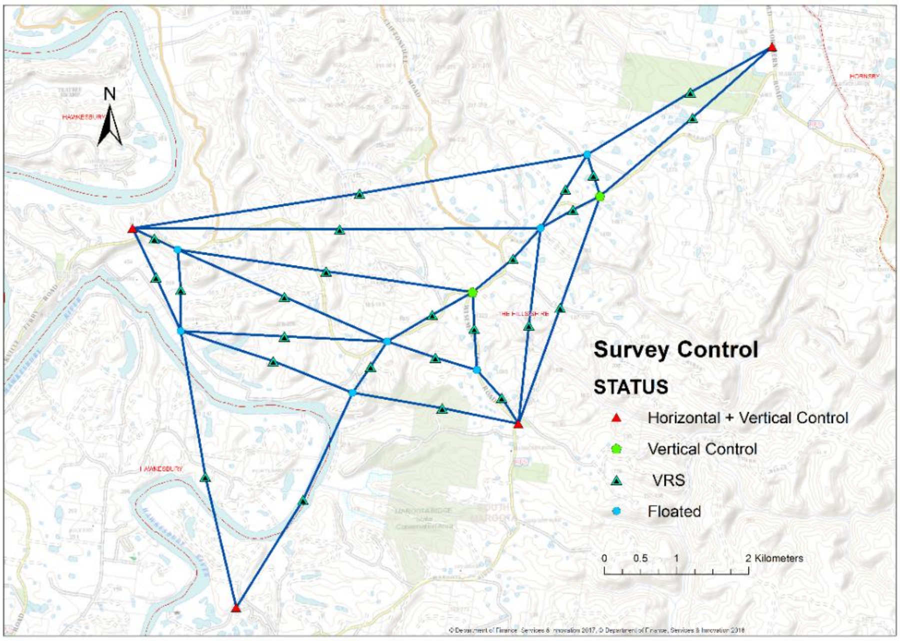

Figure 3: Network design for the VRS method with survey control configuration.

4 DATA PROCESSING

GNSS baselines were processed using Leica Geomatics Office (LGO) (Leica Geosystems, 2017). Each baseline was carefully examined, with short observations and noisy data removed. GeoLab (BitWise Ideas, 2019) was used to perform the least squares network adjustments.

An important consideration must be taken in the implementation of this method. In the least squares adjustment (LSA) of a closed-loop survey, it is essential that no trivial baselines exist within the network, as explained by Reilly (1997). Since each VRS generated within the area of a typical survey is most likely interpolated from the same dataset collected by the surrounding Continuously Operating Reference Stations (CORS), a single GNSS observation can only be connected to one VRS. Therefore, each line coming from a survey mark requires a new measurement.

As required by Surveyor General's Direction No. 12 (DFSI Spatial Services, 2012) and SP1 version 1.7 (ICSM, 2007), the determination of class comes from a minimally constrained LSA. This also serves as an assessment of the quality of the data, while allowing an estimate of the precision of observations to be formed and is essential in ensuring the validity of this comparison (Featherstone et al., 2001). The assignment of order is then based on the fully constrained adjustment. In this case, the adjustment provides horizontal coordinates relative to the Map Grid of Australia 1994 (MGA94), zone 56, and, following application of AUSGeoid09 (Brown et al., 2011), heights with respect to AHD.

Northing-Easting correlations were used for the input standard deviations for GNSS baselines, and not Northing-Easting-Up correlations. This reflects the differing quality in horizontal and vertical components inherent in GNSS measurements (Li et al., 2010). Furthermore, separating horizontal and vertical components will give independent variance factor (VF) values for each component. This provides greater flexibility in the adjustment of the horizontal and vertical input standard deviations and prevents one from skewing the other, with a 3-dimentional VF potentially containing an overly large vertical VF and a small horizontal VF, or vice versa, which together could pass the Chi-squared test. However, in reality the standard deviations used are not appropriate for either direction. Harvey (2016) describes the Chi-squared test as a range of acceptable values for the VF, with two-tail test limits being given by:

$$1/F_{1-\alpha/2,r2,r1} < VF < F_{1-\alpha/2,r1,r2} \quad (1)$$

where α is the significance level of the test (5%), r1 is the degree of freedom of the solution, r2 is the degree of freedom of the a priori estimate of the VF, and F is the F-statistic.

The following input standard deviations were applied to the minimally constrained adjustment of the static network:

- Horizontal: 0.005 m constant + 0.7 ppm, and 0.0015 m centring.
- Vertical: 0.015 m constant + 2.0 ppm, and 0.002 m centring.

These values resulted in a variance factor of 0.51 and a failure of the Chi-squared test. With confidence in the survey geometry and methodology, instead of lowering input standard deviations beyond realistic values, it was chosen to scale the covariance matrix by the VF in order to achieve more appropriate values for the error ellipses.

An examination of the statistical results from initial runs of the minimally constrained adjustment of the VRS method revealed that the average redundancy number for the VRS network was low, with a value of 0.27. Observations with redundancy numbers below 0.3 may have a negative effect on the strength of the network (Geoida, 2017). Furthermore, Harvey (2016) describes that small redundancy numbers can hide the effects of marginally detectable errors within the network. Low redundancy numbers in this case are the result of the VRS method adding a node between each pair of measured marks, leading to a weakening in geometry. Given that the method being tested is somewhat of an unknown quantity, it was decided to add more observations to brace these nodes and increase the strength of the network to ensure that potential measurement errors are well understood. The resulting changes in the geometry of the network are pictured in Figure 4.

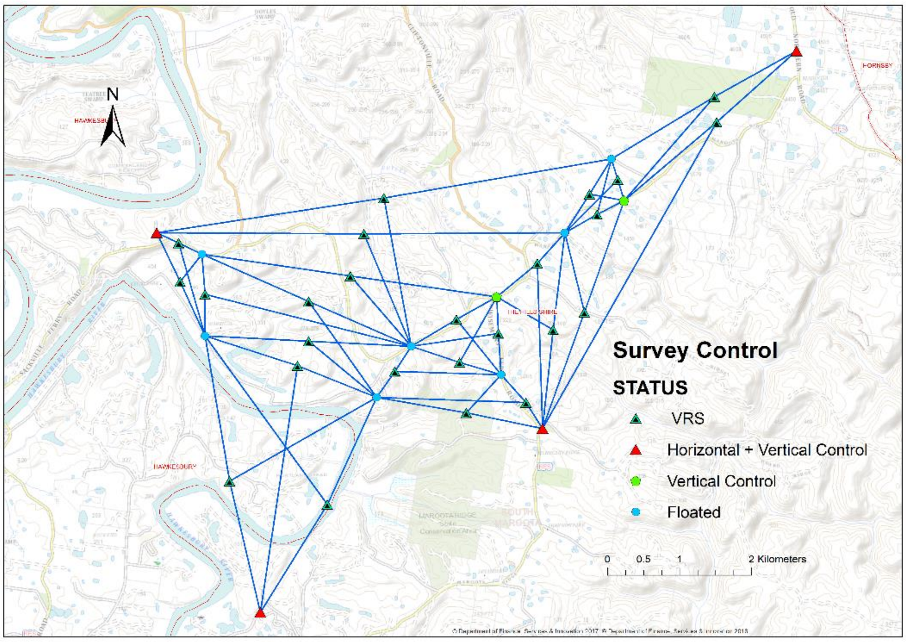

Figure 4: Network design for the VRS method with added measurements.

The addition of these bracing lines resulted in an average redundancy of 0.55, well above the value recommended by Geoida (2017). By comparison, the average redundancy for the static network adjustment was 0.56. In the adjustment of the VRS method, the ‘centring’ component of the VRS is somewhat unknown, but certainly not as precise as the centring error estimated for the set-up of a receiver. Retscher (2002) found the precision of a VRS near to a CORS to be ±20 mm for the horizontal component and ±43 mm for the vertical (99% confidence level). The adjustment process used here does not allow for differing centring errors to be implemented. However, this effect is assumed to be a constant error and will be absorbed into the constant in the estimate of the precision used.

The final input standard deviations for the minimally constrained adjustment of the VRS network were therefore:

- Horizontal: 0.008 m constant + 0.6 ppm, and 0.0015 m centring.
- Vertical: 0.020 m constant + 2.0 ppm, and 0.002 m centring.

The above values resulted in a VF of 0.85, which passed the Chi-squared test, and therefore it was decided not to scale the error ellipses.

5 RESULTS

The LSA of the static GNSS survey resulted in a class and order of B2 for both horizontal and vertical components, as computed by DFSI Spatial Services. The LSA of the survey using the VRS method also resulted in a horizontal class and order of B2, however, returned a vertical class and order of C3. In order to further investigate these results, we first examined the relative uncertainties between marks within the network as a product of each survey. Results from the minimally constrained adjustment were examined, as these form an assessment of the quality of measurements, free from potential datum distortions.

Figure 5 displays the magnitude of the semi-major axis of the horizontal relative error ellipse (REE) between each pair of marks within the network at the 2-sigma level, for both the static and VRS networks.

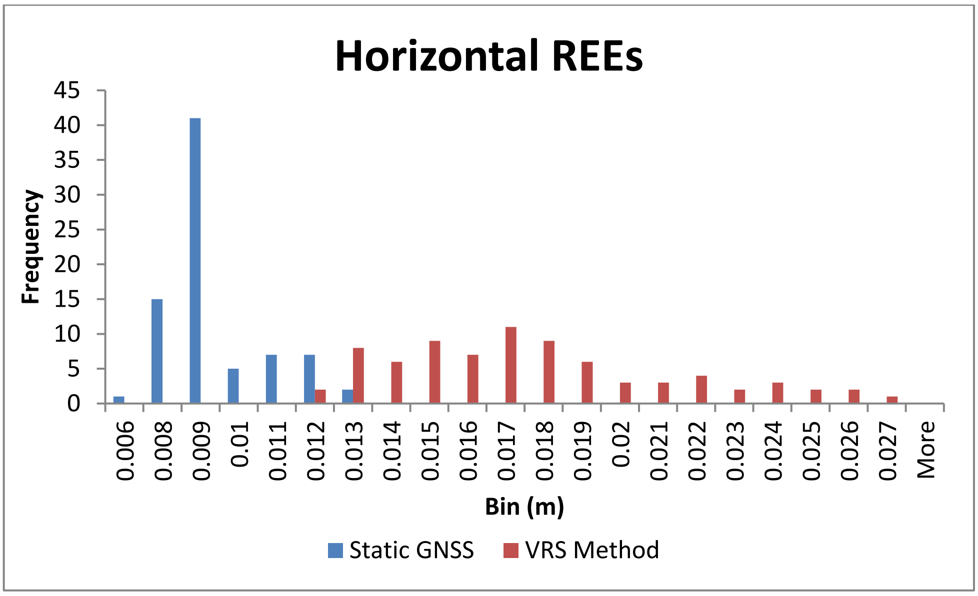

Figure 5: Comparison of the horizontal REEs resulting from each adjustment.

The amount of data in each survey is insufficient to definitively show a normal distribution of REEs, however, each dataset shows roughly the expected shape. The static GNSS network showed superior results, with the majority of REEs tightly grouped around a mean of 9 ± 2 mm. The VRS method gave a mean REE of 18 mm and showed less stability, exhibiting a larger standard deviation than the static GNSS network (with a value of ±4 mm), and also appears to show some positive skewness with a maximum value of 27 mm.

The same comparison was then made for the vertical REEs from each LSA, shown in Figure 6. Again, each set of REEs appeared to be roughly normally distributed, with the static survey provided better uncertainty results, with a mean of 19 ± 4 mm. The VRS survey resulted in a mean of 34 ± 7 mm, with the highest value being 54 mm which was not flagged as an outlier.

The computed coordinates, resulting from the minimally constrained adjustment, of the 9 horizontally floated marks and also the 7 vertically floated marks were compared between both survey adjustments. Table 1 contains a summary of the descriptive statistics, showing that both surveys provided good agreement with an overall horizontal Root Mean Square (RMS) difference of 17 mm (1σ), a median of 13 mm and a maximum difference of 39 mm. Vertically, the RMS difference was 19 mm (1σ), with a median of 14 mm and a maximum of 36 mm.

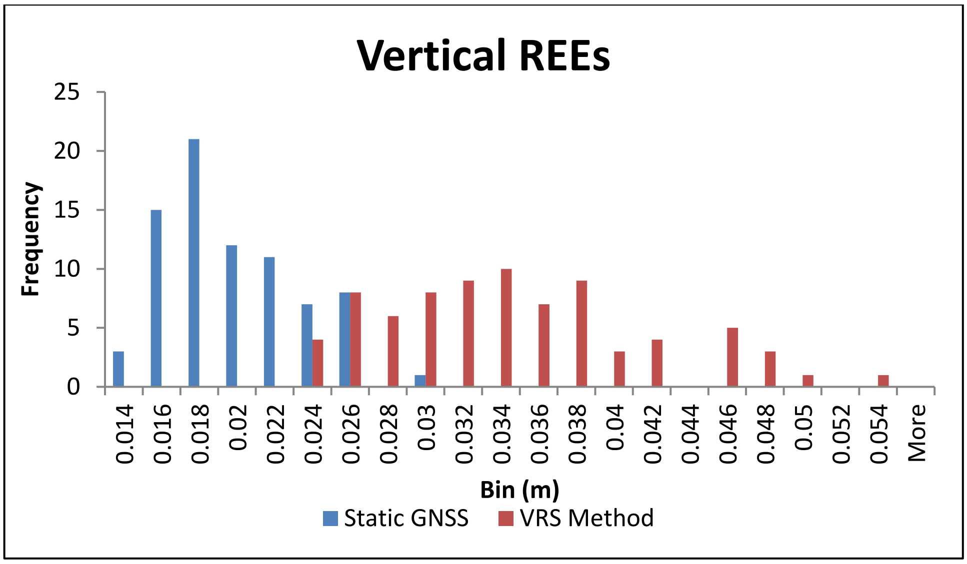

Figure 6: Comparison of the vertical REEs resulting from each adjustment.

Table 1: Descriptive statistics comparing coordinates derived from each LSA.

	Easting	**Northing**	**Horizontal**	**AHD**
RMS (m)	0.009	0.014	0.017	0.019
Median (m)	0.007	-0.010	0.013	0.014
Max (m)	0.018	0.035	0.039	0.036
Min (m)	0.001	0.003	0.005	0.005

6 CONCLUDING REMARKS

This paper has investigated the performance of an alternative method of static GNSS control survey that utilises elements of NRTK methodology to allow the survey to be performed with a single GNSS receiver. While the comparison aimed to keep survey geometry for both methods as similar as possible, it became clear that the addition of VRSs used to link observed stations introduced geometrical weakness. This weakness was then resolved with the addition of extra observations used to brace the linking VRSs in a roughly perpendicular direction.

Analysis of the LSAs of each survey network showed that, perhaps unsurprisingly, the VRS method was not able to match the performance or stability of the static GNSS survey, which resulted in mean horizontal REEs of 18 ± 4 mm, compared to 9 ± 2 mm, and mean vertical REEs of 34 ± 7 mm compared to 19 ± 4 mm, respectively. Based on these results, the adjusted coordinates compared within expected ranges, with a horizontal RMS difference of 17 mm and vertical RMS difference of 19 mm, both at the 1σ level. As this paper aimed to find a relatively rapid and resource-effective method, the measurement times of 10 minutes used are quite short for static GNSS surveys. Results could be improved by using longer observation times.

While there was a difference in quality, both surveys were able to achieve a horizontal class B, based purely on the resulting statistics. Vertically, the tested method returned a class C, compared to a class B from the static method. Given that class, as defined in SP1 version 1.7 (ICSM, 2007), is not only based on statistical results but also survey methods and procedures, the awarded class using the tested method is up for debate.

Although not able to match the results of a static GNSS survey, the results were still encouraging, and would be fit for purpose for many control surveys. Furthermore, the ability to perform a closed-loop control survey with a single GNSS receiver provides a significant resource advantage. The ability for a single surveyor with a single receiver to perform a survey of this quality, was previously not possible.

There are also other potential applications of the tested methodology. One particular application could be to augment static control surveys with extra connections, using raw observations already made, and linking them via a VRS. This could be done retrospectively without the need for more observations, provided VRS data is still available for the appropriate time intervals. This study has demonstrated a further use of pre-existing technology, which may have much more potential than is currently realised.

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