# Control Surveys: Why things are the way they are and not the way you think they should be!

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## ABSTRACT

*Control surveys can be realised in many guises, from large geodetic networks down to a set-out grid for a construction project. They all serve the same purpose, i.e. providing a base framework that will underpin some abstract or real infrastructure. This paper looks at how the rules that govern control surveys have developed and the processes used to achieve various targeted outcomes. The terms Order and particularly Class are fundamental in defining the processes associated with a control survey. New Global Navigation Satellite System (GNSS) technologies, such as Real Time Kinematic (RTK) and Network RTK (NRTK), now test our defined processes in determining Class and Order. The new Surveyor General's Direction No. 12 "Control Surveys and SCIMS" presents methods to accommodate these technologies to achieve Class C. These new technologies appear to be simple, accurate and productive but in a regulated environment things are not as simple as they appear. Rules still apply, and if followed correctly the desired outcomes can be achieved. Even so, for many surveyors, the new paradigm of absolute position observation versus relative measurement is indeed a "leap of faith". Hopefully, this paper will promote the reader to think outside the square when conducting a control survey because things are not always as they appear!*

**KEYWORDS**: *Class, Order, control surveys, GNSS, SCIMS.*

## 1 INTRODUCTION

What are control surveys? Most surveys are control surveys of some specification or standard; the keywords here are specification and standard. Generally, control surveys provide a framework that meets a standard that is required for a particular outcome. The International Terrestrial Reference Frame (ITRF, see Altamimi et al., 2011) is a global datum and can be considered as a global control survey, but this is not really how it is perceived. It is not driven by a set of formalised specifications, but nonetheless it is an extremely precise realisation of monuments on the earth's surface. For a review of coordinate systems, datums and associated transformations the reader is referred to Janssen (2009).

On the other end of the scale, a simple builder's profile is also based on a control survey of sorts. Usually, a *surveyor* will peg out the house position with offset pegs and the builder will place his string line profiles over them. The general requirement is that the set-out complies with the building plan.

So, between the global-scale ITRF and the simple house set-out the scope and size of control surveys can be quite variable. This paper is focused on the control surveys that are defined in Special Publication 1 (SP1, see ICSM, 2007) and the soon to be released Surveyor General's

Direction No. 12 "Control Surveys and SCIMS" (draft available online, see LPI, 2012a). These control surveys are the types of surveys that result in the realisation of a datum and involve terms like station occupations, redundancy, network design, variance factors, Class, Order, observation variance, error ellipses and many other terms that surveyors are not always comfortable or familiar with. As well as these terms, there are also new technologies and methodologies which challenge the concept of control survey requirements as defined by existing directions. This paper hopes to demystify some of these concepts and separate technology from standards where this area has become somewhat blurred.

## 2 STANDARDS

Why do we have standards? Without standards the control of quality outcomes cannot be guaranteed. Today, accepted standards define most things in our day-to-day environment. There are standards for electrical work, plumbing, motor vehicle design, building, television advertising – the list goes on and on.

In survey work, standards define accuracy of outcomes. For control surveys, the standards are empirical values referred to as Class, Order and Uncertainty (the implementation of which has been challenging due to aspects of the concept, see Roberts et al., 2009). Specifications on the other hand, provide the processes needed to achieve standards, such as equipment and operational procedures.

### 2.1 Class

Class is the term/value we assign to a survey and subsequently the points or stations in that survey that defines the survey as achieving a certain standard. The determination of Class is defined in SP1 (ICSM, 2007) as:

"Class is a function of the planned and achieved precision of a survey network and is dependent upon the following components:

- the network design,
- the survey practices adopted,
- the equipment and instruments used, and
- the reduction techniques employed,

all of which are usually proven by the results of a successful, minimally constrained least squares network adjustment computed on the ellipsoid associated with the datum on which the observations were acquired."

"The allocation of Class to a survey on the basis of the results of a successful minimally constrained least squares adjustment may generally be achieved by assessing whether the semi-major axis of each relative standard error ellipse or ellipsoid (i.e. one sigma), is less than or equal to the length of the maximum allowable semi-major axis ($r$) using the following formula:

$$r = c\,(d + 0.2) \tag{1}$$

where
$r$ = length of maximum allowable semi-major axis in mm,
$c$ = an empirically derived factor represented by historically accepted precision for a particular standard of survey,

$d$ = distance to any station in km."

The values of c assigned to various Classes of survey are listed in Table 1.

Table 1: Classification of horizontal control surveys according to SP1 (ICSM, 2007).

| Class | C (for one sigma) | Typical applications |
|---|---|---|
| 3A | 1 | Special high precision surveys |
| 2A | 3 | High precision national geodetic surveys |
| A | 7.5 | National and state geodetic surveys |
| B | 15 | Densification of geodetic survey |
| C | 30 | Survey coordination projects |
| D | 50 | Lower Class projects |
| E | 100 | Lower Class projects |

This appears to be a fairly uncomplicated definition. The first part is straight forward: terms like equipment and instruments, reduction techniques and survey practices are all familiar terms and descriptions. These terms are all subject to certain specifications and reductions. For example, does the Class require a rigorous formula to reduce measurements? Is a minimum number of occupations of stations specified? Is instrument certification a requirement?

The next part of the definition uses words like least square adjustment, semi-major axis and relative standard error ellipse. It is this part of the definition where things start to get disinteresting. A lot of people turn off at this part. In order to meet the requirements of the definition, the surveyor needs good least squares adjustment software and good fundamental understanding of what this part of the definition is alluding to.

Equation 1 defines the 1-sigma ($1\sigma$) maximum semi-major axis of the relative error ellipse for two stations a given distance apart where $d$ is in kilometres. As a rule-of-thumb, the value $c$ in Table 1 can be interpreted as a parts-per-million (ppm) value. For example, for a Class 2A survey where the distance between adjacent stations is 2 km, the maximum allowable size of the semi-major axis of the relative error ellipse is about 3 ppm or 6 mm. Similarly, the maximum Class C relative error ellipse over the same distance is about 30 ppm or 60 mm.

An important word in the definition of Class is *successful* in referring to the least squares adjustment. This generally implies that the adjustment Variance Factor (VF) is close to unity, that in-turn suggests a normally distributed set of observation residuals. This also indicates that the observation variance estimates are correct so that the relative error ellipse sizes are 'true'. It also indicates that you have confirmed that your observations agree with themselves as a stand-alone survey.

### 2.2 Order

The Order of a survey is an evaluation of semi-major relative error ellipses which result from constraining the least squares adjustment to fixed coordinates. SP1 (ICSM. 2007) defines Order as:

"Order is a function of the Class of a survey, the conformity of the new survey data with an existing network coordinate set *and* the precision of any transformation process required to convert results from one datum to another. Stations in horizontal control surveys are assigned an Order commensurate with the Class of the survey and the conformity of the survey data with the existing coordinate set. The Order assigned to the stations in a new survey network following constraint of that network to the existing coordinate set may be:

a. not higher than the Order of existing stations constraining that network, and
b. not higher than the Class assigned to that survey."

The highest Order that may be assigned to a station from a survey of a particular Class is shown in Table 2.

Table 2: Relationship between Class of a survey and the highest Order to be assigned (ICSM, 2007).

| Class | Order |
|---|---|
| 3A | 00 |
| 2A | 0 |
| A | 1 |
| B | 2 |
| C | 3 |
| D | 4 |
| E | 5 |

As the concept of Order is based upon the Class of the station as well as the fit of the survey network to the existing coordinate datum, the Order correlated to Class alone may be degraded by its fit to the existing coordinate set or as a result of the configuration of the ties used to constrain it to the existing datum. The allocation of Order to a station in a network, on the basis of the fit of that network to the existing coordinate set, may generally be achieved by assessing whether the semi-major axis of each relative standard error ellipse or ellipsoid, with respect to other stations in the fully constrained network, is less than or equal to the length of the maximum allowable semi-major axis. This technique is identical to that employed in the determination of Class and makes use of the same formula (Equation 1). The values of $c$ for various Orders of survey are shown in Table 3.

Table 3: Order of horizontal control surveys (ICSM, 2007).

| Order | C value (for one sigma) |
|---|---|
| 00 | 1 |
| 0 | 3 |
| 1 | 7.5 |
| 2 | 15 |
| 3 | 30 |
| 4 | 50 |
| 5 | 100 |

The derivation of Order for a station within a constrained least squares adjustment follows a similar process to that of determining Class. The above definition of Order does not include the wording "successful least squares adjustment". But the evaluation of Order requires similar techniques as Class to achieve an adjustment VF of unity. It may be necessary to downgrade your observation variances to fit to the constrained coordinates and achieve that VF value near unity, which then implies a normalised residual set and relative error ellipses which are 'true'. You have determined the Order of your survey in terms of its constraints. It is quite possible to determine that a survey is Class 2A but Order 4.

Assigning Order to a mark or station "must remain within the subjective judgement of the geodesists of the relevant authority" (ICSM, 2007). This means that you have control over the Class of your survey if you follow the specifications. As long as the specifications do not change, the Class should not change. However, the assigned Order can change at the discretion of the relevant authority, but it must still comply with Table 2.

### 2.3 Class and Order for Heighting

Similar tables and formulas are used in the derivation of Class and Order for vertical survey work. There is a distinct difference in the classification of differential (spirit) levelling and heights derived by other techniques such as trigonometric or Global Navigation Satellite System (GNSS) heighting. Differential levelling is based on the formula (ICSM, 2007):

$$r = c\,\sqrt{d} \qquad (2)$$

whereas other heighting methods are tested using Equation 1. In both cases, the value of $r$ is now 1-dimensional and defined as the maximum allowable error in millimetres. The value $d$ continues to represent the distance in kilometres, while $c$ is determined according to Table 4. Note that for non-differential levelling the values for $c$ are the same as for horizontal Class.

Table 4: Values of ‘c’ assigned to each Class of survey (ICSM, 2007).

| **Differential Levelling** $r = c\sqrt{d}$ | | **Trigonometric and GNSS Heighting** $r = c\,(d+0.2)$ | |
|---|---|---|---|
| **Class** | **C (for one sigma)** | **Class** | **C (for one sigma)** |
| L2A | 2 | 2A | 3 |
| LA | 4 | A | 7.5 |
| LB | 8 | B | 15 |
| LC | 12 | C | 30 |
| LD | 18 | D | 50 |
| LE | 36 | E | 100 |

### 2.4 Uncertainty

Uncertainty is a relatively new concept in terms of control surveys, even though it is discussed in SP1. There are two types of uncertainty, i.e. positional and local.

SP1 (ICSM, 2007) defines Positional Uncertainty (PU) as “the uncertainty of the coordinates or height of a point, in metres, at the 95% confidence level, with respect to the defined reference frame. The reference frame *must* be described in the metadata. In Australia, the currently defined reference frame for horizontal positions is GDA94 and for heights is AHD. In New Zealand, the currently defined reference frame for horizontal positions is NZGD2000. Positional Uncertainty is reported as the total uncertainty propagated from the zero order network (the AFN in Australia) or, in case of AHD heights, the total uncertainty propagated from the AHD tide gauge bench marks.”

This definition means that as you drill down through network layers, the Positional Uncertainty of a point grows larger. The point’s uncertainty is an accumulation of observational error. This is not too difficult to implement but it requires knowledge of point error ellipse sizes of each and every constraining point if it is derived by layers. It can also be derived by adjustment if the entire point network is run as a single network adjustment, an approach which is being proposed for the planned new static Australian datum (tentatively called GDA2020). Positional Uncertainty is a term proposed to replace Class.

Local Uncertainty is the term used to represent/replace Order. SP1 (ICSM, 2007) defines Local Uncertainty (LU) as “the average measure, in metres at the 95% confidence level, of the relative uncertainty of the coordinates of a point(s), with respect to the survey connections to adjacent points in the defined frame. Each relative uncertainty used to determine this average is the uncertainty between the coordinates of two related points.”

The implementation of Local Uncertainty is a little more difficult to implement (Roberts et al., 2009). The rule with Class and Order is that the Order can never exceed the Class. In the case of uncertainty, LU will exceed (i.e. be better than) PU. Survey projects should stipulate a LU in lieu of PU to define the required survey standard. This is the reverse of the Class and Order rule.

## 3 SPECIFICATIONS

As mentioned earlier, specifications provide the processes needed to achieve standards. SP1 (ICSM, 2007) provides a vast amount of detail about specifications for various Classes of survey. The new Surveyor General’s Direction No. 12 (LPI, 2012a) is not as specific but targets the requirements to achieve Class C and meet submission standards for inclusion in the Survey Control Information Management System (SCIMS, see LPI, 2012b) that is maintained by Land and Property Information (LPI), a division of the NSW Department of Finance & Services.

SP1 contains specification tables outlining requirements to achieve various Classes for:

- Astronomical azimuth observations
- Electronic distance measurement (EDM)
- EDM reduction procedures
- Horizontal angle measurement
- Differential levelling equipment characteristics
- Differential levelling equipment testing
- Differential levelling equipment procedures
- Differential levelling reduction procedures
- EDM height traversing equipment characteristics
- EDM height traversing equipment testing
- EDM height traversing observation procedures
- EDM height traversing reduction procedures
- Trigonometric heighting observation requirements
- Global Positioning System (GPS) method vs. Class
- Real Time Kinematic (RTK) recommended processing requirements
- GPS data attributes for “absolute” positioning
- Tables for inertial survey systems
- Tables for horizontal control surveys by photogrammetry

SP1 also contains sections on station occupation, optimisation and network design, network adjustment assessment, datum transformations, recommended marking practices and recommended documentation practices. All these specifications and guidelines provide a pathway to achieving desired Class and Order outcomes.

## 3.1 Specifications and SCIMS

The new Surveyor General's Direction No. 12 (LPI, 2012a) draws on the principles outlined in SP1 (ICSM, 2007). The Direction provides a guide as to what LPI requires before it will place coordinates, heights and quality of survey monuments on public record in the Survey Control Information Management System. More specifically, it outlines the minimum requirements for LPI to place coordinate values on survey marks in SCIMS at an established level, i.e. horizontal Class C and vertical Class B or LD or better.

An important aspect of this Direction refers to consultation: Details of LPI's full requirements and the interpretation of this Direction *must* be discussed *and* agreed with an LPI Senior Surveyor *prior* to commencement of *control* surveys *to be placed on public record*. The document addresses all aspects required by LPI in the determination of at least Class C horizontal and Class B or LD vertical surveys. These are summarised in the following sections.

### *3.1.1 Assigning Class*

This is the most technical element of the control survey process. Assigning Class is the result of the survey meeting the required specifications and practices and passing the required statistical analysis tests.

### *3.1.2 Mark Placement*

The quality of marking impacts directly on the determination of a survey's Class. It is even more significant in assigning Order. Surveyor General's Direction No. 1 (LPI, 2009) details different types of approved permanent marks. At this time, there is no Class associated with different mark types. The effective Class of a star picket in soil and a concrete observation pillar can be the same! LPI considers that mark stability is a significant element in the determination of Class and Order. Beware that poor mark location will impact on the assigning of Class.

### *3.1.3 Equipment*

Instrumentation must be able to deliver the appropriate precision for the desired Class. Class C requires distance measuring instrumentation that can measure to better than 30 ppm. A 5" total station meets Class C, while an EDM which has a measurement standard deviation of 5 mm + 5 ppm can achieve Class B. Note that a $3^{rd}$ order level may produce results which look like Class LA but it is still Class LC.

### *3.1.4 Network Design and Geometry*

Surveyor General's Direction No. 12 is mainly concerned with the determination of Class. However, without proper network design and geometry, and connections to existing SCIMS control marks, an appropriate Order cannot be determined. Therefore, LPI requires that connections to existing local control in and adjacent to the survey must be part of the design.

Surveys should not be over-observed or over-specified. Observations should be made between adjacent marks. Strong survey networks are characterised by connections between adjacent marks and good geometrical design. The network design should determine coordinates by interpolation, not extrapolation.

#### *3.1.5 Observations*

The Direction addresses issues with both terrestrial and satellite-based observations. Terrestrial observations should meet the required specifications for the desired Class. It is extremely important that observations are in reduced sets, both directions and distances. The assigning of Class is based on the characteristics of reduced data, not the evaluation of hundreds, if not thousands of individual pointings! Definitions of reduced sets or groups are available in SP1.

Distances need to be clearly defined as their type:
- Spatial
- Ground at a given height
- Mean sea level
- Ellipsoidal

LPI requirements for GNSS observations are extensive. Important issues are log sheets containing checked heights of antenna, start times, station labels, file names, etc. LPI requires that all marks be double occupied for Class C. In order to avoid scale issues, the best orthometric/ellipsoidal height, the current AUSGeoid model (AUSGeoid09, see Brown et al., 2011) and best known coordinates are used to seed processing. Absolute antenna models are particularly important when there is a mix of model types which occurs when using CORS networks or mixtures of receiver/antenna types (Janssen and Haasdyk, 2011a).

#### *3.1.6 Computation and Adjustment*

LPI strongly recommends that submissions have been subject to a least squares adjustment to resolve any issues associated with the work. Observation data should be submitted in an organised and unambiguous digital format. The submitted data must also be supplied in the form of an input file to a least squares adjustment. This requires that direction/distance data be reduced to appropriate reduced/abstracted sets. Realistic standard deviations should be applied.

Provided the submitted data is in an acceptable format and a copy of the least squares adjustment input file is supplied, LPI will perform its own least squares adjustment of the data using its own internal packages.

It is essential that support information is supplied that justifies any non-standard parameters or variances applied within the submitted adjustment. These can include re-weighting/rejection or scaling of observations, solving for rotational and scale parameters or scaling of error ellipses.

#### *3.1.7 Survey Report*

A survey report is essential if the submission is to be included in the SCIMS database. The Direction states that the report should include information on:
- The overall job, including purpose, background and intent.
- Fieldwork equipment, observation techniques, sketches, photographs, etc.
- Data processing, including software used and options applied.
- Network design and geometry.

- Adjustment, including software used, options applied, constraints, analysis and results.
- Recommendations for Class.
- Data archive, presentation and formats.
- Submission statement.

If available, digital diagrams should be included in the submission. In order to allow submissions of high quality, LPI provides a survey report template and a sample report, available at http://www.lpi.nsw.gov.au/surveying/surveying_services/survey_information.

### *3.1.8 Check List*

A check list is included in the Direction to ensure that submissions are complete and meet LPI requirements. This check list summarises the requirements and guidelines for externally sourced data of control surveys to be included in SCIMS at an "established" level. This check list must be completed and signed as part of the submission.

## 4 ACHIEVEING THE DESIRED CLASS

The attainment of a desired Class is the result of using appropriate observation techniques, suitable equipment, correct reduction processes, suitable network geometry and finally the passing of tests based on Equation 1 and Table 1. If everything is correct, the least squares adjustment has a variance factor (VF) of unity (or close to), and the observation standardised residuals should be normalised and fall under a bell curve. If this is the case, then the sizes of the relative error ellipse semi-major axes are "true".

Surveyor General's Direction No. 12 refers to a particular table a number of times. This table provides a guide to the achievable Class of a survey, given the expected sizes of the relative error ellipses and the distance between adjacent stations (Table 5). This is a very important aspect of control survey work. As the distance between adjacent marks becomes smaller, the achievable Class for a particular instrument specification becomes lower.

The size of the error ellipse of a point is governed by the standard deviations (STD) of the observations which derive that point. For example, these could include an angular STD of 3", an EDM distance STD of 3 mm + 3 ppm or a GNSS vector STD of 10 mm + 1 ppm. If these values produce a VF close to unity, then the observation residuals are normalised and the error ellipses are "true".

If the VF is not close to unity, then the error ellipses are "not true". The sizes of error ellipses are directly related to values of the observation STDs, regardless of the VF. Some adjustment packages allow the user to scale the error ellipses by the VF, but this is bad practice in adjustments where multiple observation types are used, particularly 3-dimensional adjustments.

Table 5: Class derived from station density and point error ellipse size (at one sigma). The relative error ellipse size used in the determination of Class is stated in parentheses.

| Station Density (km) \ Point and (Relative) Error Ellipse | 0.005 m (0.007 m) | 0.010 m (0.014 m) | 0.015 m (0.021 m) | 0.020 m (0.028 m) | 0.025 m (0.035 m) | 0.030 m (0.042 m) | 0.035 m (0.049 m) |
|---|---|---|---|---|---|---|---|
| **0.1** | C | D | E | E | – | – | – |
| **0.2** | C | D | E | E | E | – | – |
| **0.4** | B | C | D | D | E | E | E |
| **0.6** | B | C | C | D | D | E | E |
| **0.8** | A | B | C | C | D | D | D |
| **1** | A | B | B | C | C | D | D |
| **2** | A | A | B | B | C | C | C |
| **5** | 2A | 2A | A | A | A | B | B |
| **10** | 3A | 2A | 2A | 2A | A | A | A |

Table 5 is also independent of the instruments and/or methods used. The highlighted cell is the achieved Class if two adjacent marks 600 m apart with point error ellipses of 0.015 m (i.e. a relative error ellipse of 0.021 m) are tested.

Performing the test in this example for Class 2A using Equation 1, $c = 3$ and $d = 0.6$, so the semi-major axis of the relative error ellipse (REE) must be less than 0.0024 m. Clearly, the 0.021 m semi-major axis of the REE is greater than 0.0024 m, i.e. the test fails at Class 2A. Testing for Class B, $c = 15$ and $d = 0.6$, resulting in a REE of 0.012 m. Obviously, 0.021 m is larger than 0.012 m, i.e. the test also fails at Class B. Similarly, the test value for Class C is 0.024 m, and 0.021 m is less than 0.024 m, i.e. the test passes at Class C. Whether or not this is a valid method of determining Class at these station densities may be debateable but it is the current standard.

As geodetic surveys and breakdown surveys have merged, the inter-station distances have gradually reduced. Historically, control surveys began as geodetic surveys providing a national framework. These surveys were originally based on large triangulation networks with painstakingly measured baselines at various locations to control scale. Azimuth was controlled by stellar observations (Laplace) at various locations. These networks were observed with 1”-2” instruments. Accepting that the results were statistically acceptable, then the geodetic network achieved something near Class A, i.e. about 7 ppm. The GDA94 re-adjustment included quality EDM and GPS baselines which improved the overall result to 3 ppm or Class 2A.

As the amount of breakdown surveys have reduced the inter-station distances and the quality of measurement has improved, control surveys are migrating from the macro scale to the micro scale. The downside of this development is that for most linear measurements there are two components, a constant noise value and a distance dependent noise value (stated in ppm). As inter-station distances decrease, it is the constant noise value which restricts the use of particular instrument types to achieve certain Classes. Reflecting on Table 5, it is easy to recognise the challenges for deformation monitoring applications in reducing the size of errors associated with observations. Observation pillars eliminate centring errors, the best instrumentation is required, and network geometry plays an important role.

The constant noise value will eliminate particular instrument types for various Classes at certain station densities. An instrument with the measurement specification of 1 mm + 5 ppm is more suitable for high-density work than equipment which delivers 7 mm + 0.7 ppm. However, at lower station densities the latter instrument performs better.

### 4.1 Quality of Measurement

Standards and specifications are also about traceability and responsibility, that is why there are standards for almost everything in modern living. Traditional survey instruments operate autonomously, are self-contained and can be calibrated. A total station will deliver horizontal angles, vertical angles and measured distance without the need for any external requirements other than a power supply and a reflection of the signal.

Equipment manufacturers generally supply an accuracy statement. The following has been extracted from a Leica Viva TPS datasheet – note the superscripts:

**Angular Measurement**
Accuracy Hz, V[1] 1'' (0.3 mgon), 2'' (0.6 mgon), 3'' (1 mgon), 5'' (1.5 mgon)
Distance Measurement Distance Measurement (Prism)

| | |
|---|---|
| **Range**[2] | |
| Round prism (GPR1) | 3500 m (12,000 ft) |
| 3 Round prisms (GPR1) | 5400 m (17,700 ft) |
| 360° prism (GRZ4, GRZ122) | 2000 m (7,000 ft) |
| 360° mini prism (GRZ101) | 1000 m (3,300 ft) |
| Mini prism (GMP101) | 2000 m (7,000 ft) |
| Reflective tape (60 mm x 60 mm) | 250 m (800 ft) |
| **Accuracy**[3,4] / Measurement Time | |
| Standard | 1 mm + 1.5 ppm |
| Fast | 3 mm + 1.5 ppm |
| Tracking | 3 mm + 1.5 ppm |
| Averaging | 1 mm + 1.5 ppm |

[1] Standard deviation ISO 17123-3
[2] Overcast, no haze, visibility about 40 km; no heat shimmer
[3] Standard deviation ISO 17123-4
[4] To round prism GPR1

This is the expected measurement accuracy of the instrument according to the manufacturer. Estimates of centring accuracy and atmospheric effects must be added, considering that 1ºC is equivalent to 1 ppm, and 3 mbar is equivalent to 1 ppm. It is important to note that, depending on the length of the line, temperature and atmospheric pressure can be significant sources of error!

GNSS equipment cannot be calibrated since it does not operate autonomously. Results are dependent on a number of components. The control segment, the space segment and the user segment were all initially designed to provide a single point position. The survey component is reliant on these segments to provide information allowing the relationship (spatial vector) between two or more receivers operating simultaneously to be derived. The final component is processing software used to actually derive the spatial relationships for survey applications.

This has now been developed to the point where the spatial component is delivered in real time through the instrument interface, e.g. via single-base RTK or Network RTK utilising a continuously operating reference station (CORS) network. How do you calibrate this process?

LPI has used GNSS techniques since 1987. It has built a vast repository of GNSS baseline observations. Initially measured lengths were of geodetic nature over very long distances. This experience enabled LPI to develop a 'feel' for what appropriate observation variances would be, particularly the distance dependent (ppm) component. As measured distances became shorter, the constant component of the baseline measurement emerged. Consequently, although not calibrated, LPI uses GNSS measurements with confidence, using manufacturers' figures only as a guide. The same approach is taken by LPI in its development of positional observation variances that are now emerging with tools like CORSnet NSW (Janssen et al., 2011).

### 4.2 Relative Measurement

The common use of GNSS today has seen the introduction of non-familiar techniques and processes in the determination of coordinates. Traditional control survey techniques are modelled on the relative measurements between adjacent stations. Relative error ellipses are computed in the least squares solution based on the propagated observation variances. So, in a minimally constrained adjustment with minimal redundancy, the size of point errors increases with distance from the single constraint. Redundancy helps to reduce the size of error ellipses.

A typical relative measurement between two marks based on terrestrial observation techniques (in this case a direction and a distance) is shown in Figure 1. The ellipse is flattened because in this case the precision of the distance measurement is better than the directional measurement. Note that a standard deviation of 1" in direction is equivalent to 5 ppm! The associated error will be even greater when centring and atmospheric errors are taken into account. Modern distance measurement equipment generally provides distance dependent error components of well below 5 ppm, while the constant error components are typically below 3 mm.

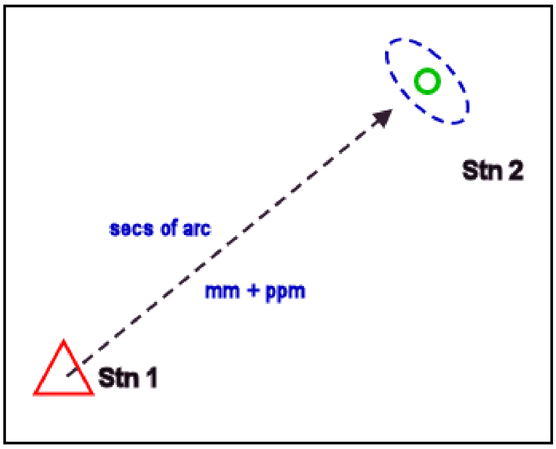


Figure 1: Error ellipse from a relative measurement.

The same model can be applied to GNSS baseline measurements or those GNSS measurements that are based on a relative measurement from one point to another. This is generally referred to as static GNSS measurement and implies that there is a difference in coordinates from one station to another. It is also considered to be an independent measurement. In the case of GNSS, the error ellipse around Stn 2 would be circular since the standard deviation of the Easting and Northing components is known to be of the same magnitude.

Using this relative measurement technique, a network of observations can be constructed. By including closing measurements and redundant observations, estimates of the observation precisions can be determined (Figure 2). This leads to the classification process of observation standard deviations, standardised residuals, variance factor near unity, and therefore error ellipse information that is "true".

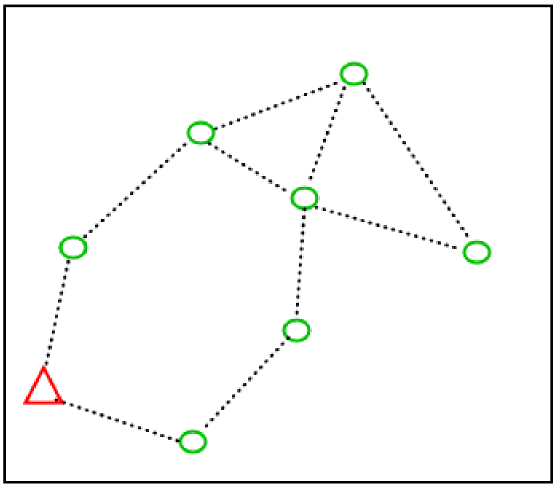

Figure 2: A simple relative observation network.

This approach has been the traditional model that defines control surveys. Its strength lies in its internal redundancy and the feedback that relative observations provide. It should also be pointed out that increasing the number of observations into a point will reduce the size of the error ellipse since *redundancy increases confidence*.

The Class of the survey in Figure 2 would be determined by the sizes of the relative error ellipses between *all* stations, not just those observed! This leads to a very common scenario of using two control stations (Figure 3).

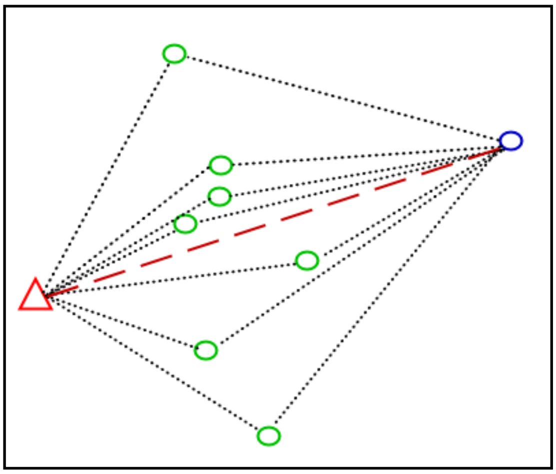

Figure 3: A network with two control stations.

Figure 3 illustrates a fairly common procedure where remote/robotic terrestrial equipment or RTK/NRTK GNSS is employed. It can be seen that this network meets a number of Class C requirements specified in SP1 and the Surveyor Generals Direction No. 12. Where it can fail is in the relative error ellipse test. If the adjustment software only generates relative error ellipses *for lines observed*, then most of these type networks pass the Class test. If the distance between the red triangle and the blue circle is large in comparison to the relative distances between the green circles, then the relative error ellipses between the adjacent green circles will be large. With modern computing equipment it is simple and prudent to calculate the relative error ellipses for all possible station relationships. Again, this comes back to the station density that controls the values in Table 5. It is also based on the assumption that GNSS errors propagate at some distance dependent (ppm) value.

In order to avoid this type of situation where LPI may reclassify the Class of the survey, ensure that discussions have been held with an LPI Senior Surveyor *before* commencing the survey. This may lead to a re-think in the network design or the inclusion of inter-station distances which could be sourced, e.g., from cadastral measurements.

### 4.3 Positional Observation

This type of observation has grown out of techniques where modern equipment delivers coordinates as its observation. Again, this can be terrestrial where the instrumentation has been configured to deliver coordinates of points instead of the measurements used to derive them. However, observed positions are more typically provided with GNSS equipment. These positions can be obtained in RTK mode, using NRTK connected to a CORS network, or via Geoscience Australia's online processing service, AUSPOS (GA, 2011).

In the relative measurement survey, observations are used to derive coordinates and estimate the quality of those coordinates based on the observation variances. However, modern GNSS equipment delivers the coordinates and its *own* estimate of the quality which is generally overly optimistic (Janssen et al., 2012). Consequently, this challenges the definition of Class where the determination of Class is based on relative error ellipses. It also negates the requirements of network design and geometry, but some things still apply such as double occupations, calibrating poles and tribrachs, solution types and quality.

As illustrated in Figure 4, each of the point position observations, whether they be RTK or NRTK, have some error ellipse associated with them. A single occupation of a point will provide a coordinate, a height and some internal error estimates. A second occupation of the point at least 30 minutes later will confirm the position and provide some estimate of repeatability (Janssen and Haasdyk, 2011b). It is this repeatability of a number of different points which provides an estimate of the associated error ellipse.

It is important that a single value is adopted for all points in the survey so that the results are normalised. Once the estimated error ellipse is adopted, relative error ellipses can be calculated and the Class of the survey can be determined based on Table 5. This is a simplistic method with very little other than repeatability to determine an outcome. Since this method is completely uncorrelated, every point will have exactly the same error ellipse and every relative error ellipse will be the same.

Unlike relative measurements, in this technique a point has no relationship with its adjacent neighbours and it is never known, i.e. it is always an estimate. Surveyor General's Direction No. 12 nominates a position error estimate value of 0.02 m for point observations using CORSnet-NSW (LPI, 2012a). The quality of and confidence in this type of survey can be improved by the inclusion of other observations such as cadastral or traverse information.

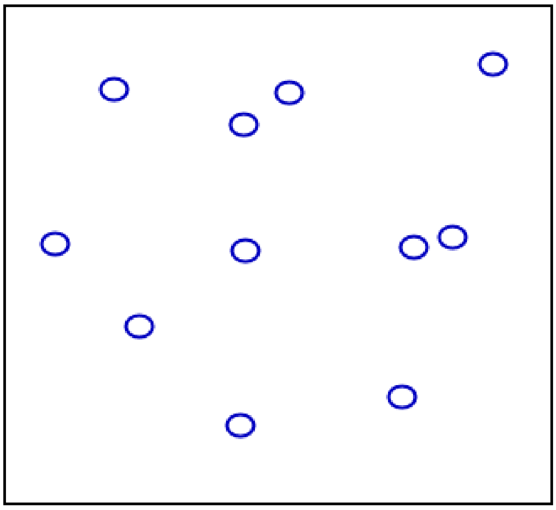

Figure 4: A position observation network.

The above scenario describes the determination of Class for position observations but is realised in the datum of the RTK base station or the NRTK datum. Since CORSnet-NSW uses the GDA94(2010) realisation of the national datum, a site transformation is required to obtain coordinates consistent with local survey ground control and local AHD71 heights (Janssen and McElroy, 2010). A simple block shift in Easting, Northing and Height is sufficient to transform RTK/NRTK observations onto local SCIMS control for surveys requiring centimetre-level accuracy, provided AUSGeoid09 is applied (Haasdyk and Janssen, 2012).

### 4.4 Adjusting to a Datum

Surveyor General's Direction No. 12 is mainly concerned with the Class of surveys and submissions for inclusion into SCIMS. It only touches briefly on the determination of Order of the surveys submitted, as the classification of Order remains solely with LPI. However, Order can only be determined by LPI if a survey is connected to existing horizontal and vertical control marks, otherwise the survey cannot be connected to the survey control network. Surveys should be connected to adjacent control points surrounding the area of the survey. It is poor practice to "jump over" existing marks if they are unsuitable for your equipment to occupy.

The relative measurement adjustment process for Order is similar to the adjustment process for Class, except now the control point constraints may increase the observation residuals, the standardised residuals are no longer normalised and the relative error ellipse information is "not true". In order to resolve these issues, the observation variances are changed to suit the quality of the control, compute a variance factor near unity and derive "true" error ellipses. These error ellipses can be tested for Order the same as Class, remembering that the Order of marks cannot be better than the Class or the Order of the constraining stations. For example, a Class B survey constrained to Order 3 stations can only yield Order 3 results!

Adjusting position observations to a datum has the same requirements. Control stations in, around and adjacent to the survey area should be occupied. Since position observations are mainly specific to GNSS surveys, the results will be 3-dimensional. Including known height points will assist in determining estimates of AHD71. Control marks need to be occupied twice, i.e. the same as unknown points, with occupations at least 30 minutes apart (Janssen et al., 2012).

## 4 CONCLUDING REMARKS

This paper has attempted to provide some insight into the control survey process, particularly in regards to the impact of satellite positioning technology. It has been difficult for many to accept that position observation is in fact a control survey; the process itself lacks the relationships between adjacent points that characterise control surveys. It is the author's view that positioning technology will be challenged in the high-density environment at the Class C level. These constraints will last some time since the fundamental measurement noise is associated with the frequency band of the satellite systems and the receiver observation resolution.

This has been somewhat negated in the past by observing longer periods to reduce the Root Mean Square (RMS) of observations. Short-term ambiguity resolution of only 1 to 2 minutes will always be subject to some noise. Improving GNSS receiver technology to observe at an order of magnitude better may overcome the noise component issue. Nevertheless, the issue of calibration will continue.

Regardless of the techniques used, the requirements of Class and Order remain the same and are "black and white". The challenge is to maintain the standards and specifications of measurement and now positioning technologies. It is increasingly important for spatial professionals to use the appropriate tools for the desired outcome. A sobering comment by Mr Les Gardner, LPI Senior Surveyor states that "it's not that the standards aren't keeping up with the technology, technology is not keeping up with the standards!"

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