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Guidelines for the use of GNSS in land surveying and mapping

2nd edition, guidance note

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RICS guidance note

2nd edition (GN 11/2010)

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Contents

RICS guidance notes

This is a guidance note. It provides advice to members of RICS on aspects of the profession. Where procedures are recommended for specific professional tasks, these are intended to embody 'best practice', that is, procedures which in the opinion of RICS meet a high standard of professional competence.

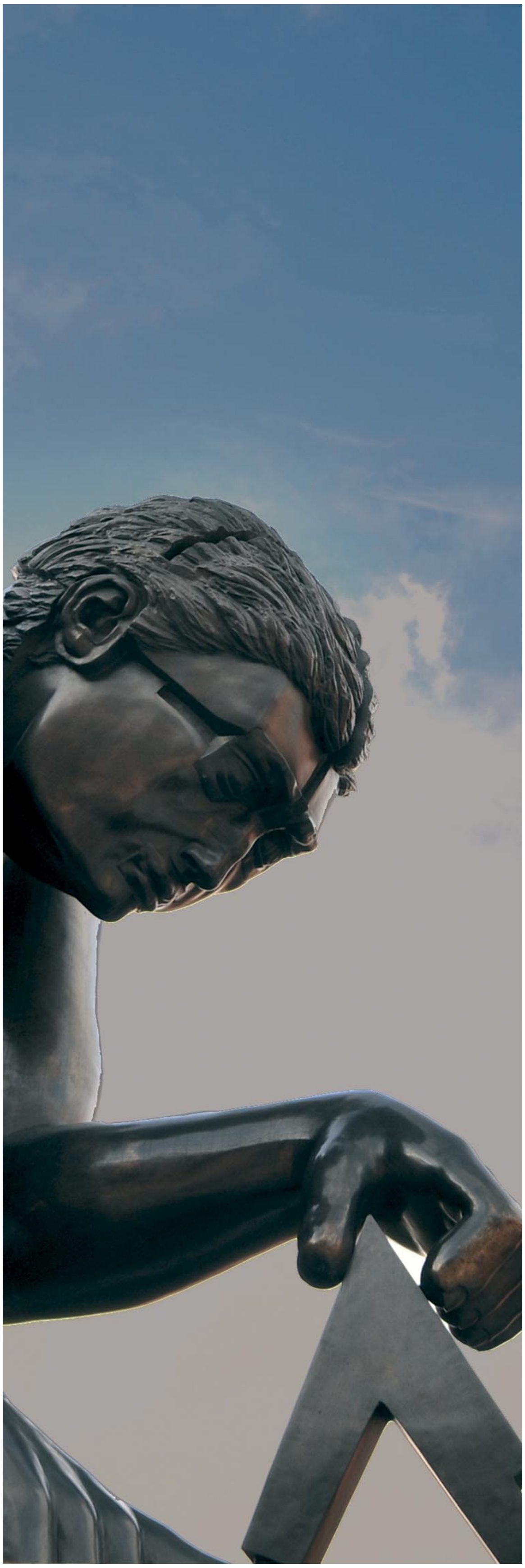
Members are not required to follow the advice and recommendations contained in the guidance note. They should, however, note the following points.

When an allegation of professional negligence is made against a surveyor, the court is likely to take account of the contents of any relevant guidance notes published by RICS in deciding whether or not the surveyor has acted with reasonable competence.

In the opinion of RICS, a member conforming to the practices recommended in this guidance note should have at least a partial defence to an allegation of negligence by virtue of having followed those practices. However, members have the responsibility of deciding when it is appropriate to follow the guidance. If it is followed in an inappropriate case, the member will not be exonerated merely because the recommendations were found in an RICS guidance note.

On the other hand, it does not follow that a member will be adjudged negligent if he or she has not followed the practices recommended in this guidance note. It is for each individual chartered surveyor to decide on the appropriate procedure to follow in any professional task. However, where members depart from the good practice recommended in this guidance note, they should do so only for good reason. In the event of litigation, the court may require them to explain why they decided not to adopt the recommended practice.

In addition, guidance notes are relevant to professional competence in that each surveyor should be up to date and should have informed him or herself of guidance notes within a reasonable time of their promulgation.



Preface

This second edition of the *Guidelines for the use of GNSS in surveying and mapping* is published by the Royal Institution of Chartered Surveyors under the aegis of the Mapping and Positioning Practice Panel (MAPPP). The guidance note forms part of a series of specifications and guidelines intended to assist all those connected with the requesting, purchase and production of surveys and mapping material at all scales, by spreading good practice and seeking to avoid duplication of effort. The MAPPP is one of the foremost technical practice panels within RICS and is comprised of private and public sector surveying and mapping industry experts, academics and survey instrument manufacturers. This broad expertise enables MAPPP professional/technical guidance and output to adhere to industry best practice.

Unlike survey specifications, this document is intended to provide best practice guidance only and is not intended to be incorporated verbatim into the text of individual contracts. However, the wording of individual paragraphs and the surveyor and client checklists can be so used, and copyright provisions are waived solely for this purpose.

There are a number of other publications related to the full range of land surveying services:

- Surveys of Land, Buildings and Utility Services at Scales of 1:500 and Larger: Client Specification Guidelines (2nd edition), 1996
- Measured Surveys of Land, Buildings and Utilities – Client Specification Guidelines (proposed 2010)
- Vertical Air Photography and Derived Digital Imagery: Client Specification Guidelines (5th edition) 2010
- Terms and Conditions of Contract for Land Surveying Services (3rd edition) 2009

MAPPP also produce a full range of geomatics client guides, including one specially on GPS RTK networks, and public guides. A full listing of relevant GPS-related RICS professional information and other publications can be found within Appendix C. All MAPPP output and further information on the panel can be found at www.rics.org/mappp

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Introduction

This guidance note has been produced to provide surveyors and their clients with guidelines for the use of **Global Navigation Satellite Systems** (GNSS) in land surveying. The first edition of these guidelines referred to (**Global Positioning Systems**) GPS, which at the time was the only constellation in operation and available to surveyors. This edition uses the term GNSS throughout, to reflect the fact that there is now more than one satellite navigation system constellation available and that there are GNSS receivers on the market that can use data from multiple constellations.

This document has been written primarily with two goals in mind:

- to provide the surveyor with a set of practical operational guidelines, which can be used when undertaking any survey that includes GNSS techniques. Sufficient information is also included to allow the surveyor to generate a set of GNSS survey procedures applicable to a survey task required by the client
- to provide the client, or purchaser of spatial information generated from a GNSS survey, with sufficient information to write a task specific specification for a GNSS survey which sets out the accuracy requirements, products and a scope of work, from which the surveyor can accurately produce a bid for the survey.

It is seldom the case that a survey will comprise GNSS techniques alone. This guidance note should be used with the appropriate client specification guidelines document for the scale of the survey. For example, a 1:500 topographic survey of a 5km pipeline route can be specified with the RICS document *Surveys of Land, Buildings and Utility Services at Scales of 1:500 and Larger*; it should be noted that this specification will be superceded by *Measured Surveys of Land, Buildings and Utilities* in 2010/11. These guidelines should then be used in conjunction to provide best practice information on the particular aspects of the survey reliant upon GNSS techniques. Surveyors may also find it useful to refer to the MAPPP client guide on GPS, 'Virtually right – networked GPS', available at www.rics.org/mappp and in the case of surveyors in Great Britain, the information on the GB National GNSS Network, available at www.gps.gov.uk

In addition to the above purposes, these guidelines can be used as a general reference document and as a practical 'operational handbook', to supplement other more academic texts on GNSS surveying.

The guidance note is divided into two parts. Part 1 serves as a summary of the important criteria that should be considered in GNSS surveying and can be read quickly to grasp the fundamental concepts and issues related to GNSS surveys. It includes summary information and actual guidelines for best practice. Part 2 is a technical explanation which develops the themes of Part 1 in a more formal context. This is primarily intended for surveyors and clients who wish to understand some GNSS theory and the technical reasons behind the good practice guidelines.

The guidelines adopt a standard nomenclature for the many terms that are found in GNSS surveying. As GNSS survey techniques have developed over time, the manufacturers, universities undertaking research and individuals involved have all adopted different and sometimes confusing terms. In particular, standard terms for survey methods have been adopted. A glossary of the technical terms is provided at the end of the document.

These survey guidelines are concerned with the land survey applications of GNSS, and do not attempt to cover specific hydrographic or aerial positioning requirements. With the rapidly advancing technological edge of GNSS surveying, not all aspects of current research and development can be covered by these guidelines. Most GNSS surveying products commercially available at the time of publication are covered within this edition.

Part 1 – Guidelines

1 The role of GNSS in surveying

The United States' Global Positioning System (GPS) and its Russian equivalent – Global Navigation Satellite System (GLONASS) are both three-dimensional measurement systems which operate through the observations of radio signals emitted by satellites in their respective constellations. The radio signals are recorded and used to determine positions. Since 1987, the orbital co-ordinate data for GPS satellites has been computed using the World Geodetic System 1984 (WGS 84), an earth-centred and earth-fixed co-ordinates system. The corresponding GLONASS co-ordinate system is PZ 90-2. Receivers that can observe data from satellites from both available constellations are now common; these guidelines cover use of these receivers as well as older units that can receive only GPS signals.

It should be noted that further GNSS systems are in development around the world: most notably, the European-based Galileo system and the Chinese COMPASS system. Time frames for deployment vary, but receivers that are built to deal with these systems are already available, although many technical and integration issues remain to be overcome. Both GPS and GLONASS have modernisation and upgrade programmes for replacement satellites and additional frequencies.

1.1 GNSS in perspective

GNSS has been used extensively by land surveyors since the late 1980s, primarily for geodetic control networks and for photo control. As systems have become more compact, more technologically advanced, easier to use and with a full complement of satellites enabling 24-hour usage, the diversity of surveying applications has increased significantly. GNSS systems are now available for many surveying and mapping tasks, including establishing control, setting out, real-time deformation monitoring, on-board camera positioning for aerial photography; the list is continually growing.

GNSS is a tool for fixing positions, and a variety of systems are available, depending on the accuracy of the points to be fixed. They range from low-cost systems with a positional accuracy of tens of metres, to high-cost geodetic survey systems able to determine positions to the sub-centimetre level. For survey accuracies, it is essential that hardware and software specifically designed for survey applications are used; these should always be utilised in the manner for which they were designed.

WGS 84 serves as a global mathematical reference frame for GPS, but in itself it is imprecisely defined. For survey applications a more accurate version of WGS 84 exists. Internationally this is termed ITRSxx, where xx relates to the epoch (date) of the co-ordinate system. Thus ITRS89 is the co-ordinate system based on the date of 1989. (Regional derivatives also exist – ETRS89 for Europe, for example.) For clarity, ITRS89 is used throughout this document, but the regional current epoch version, applicable to location, should be substituted whenever it is read. Note that the co-ordinate grids and datums used for survey and mapping projects can be a variety of differing types, and it is usual to transform GNSS co-ordinates to a local or national system. (An extensive global collection of transformation parameters and reference frameworks can be found at www.epsg.org/geodetic.html).

A number of public domain information and GNSS data sources are available specifically for GNSS land surveying usage, primarily on the internet. In particular the operational state of the system and information from various national mapping agencies is available. GNSS data is also available in the form of base station data and precise orbital elements. Many national mapping agencies and commercial organisations are developing active and passive reference stations and network RTK reference station networks.

One of the basic tenets of surveying is 'working from the whole to the part', and GNSS is no different from any other form of survey in this respect. Points of detail are measured within a control framework just as in traditional surveys. GNSS is not a total, unqualified, revolution in land surveying: optical instrument techniques still have an important role. There is a wide variety of survey applications which are unsuitable for GNSS, mainly due to the limiting factor that GNSS requires a clear view of the sky to receive satellite signals.

1.2 Survey types

There are essentially three types of survey when using GNSS techniques. Guidelines for each are given in the paragraphs and tables on the following pages. The three types can be split conveniently into different accuracy bands:

- control surveys – high accuracy
- detail surveys – medium accuracy
- positioning – low accuracy.

1.2.1 Control survey guidelines

A GNSS control survey is used to form the main co-ordinate framework for a project, as in a classical survey. Control surveys are typically at sub-centimetre accuracy. The number of stations, their location and spacing will be determined by the purpose of the control, the accuracy of the eventual survey and the type of GNSS equipment available for the project.

See **Table A**: Control survey guidelines (p. 8).

1.2.2 Detail survey guidelines

GNSS provides an excellent tool to quickly, accurately and reliably position points of detail, for example the points or features which may need to be mapped as part of the survey, within the confines of an area surrounded by the control survey. Detail surveys typically have a requirement for accuracy of between one and ten centimetres. Some applications, however, for example in utility asset mapping, require accuracies in the 10 to 30-centimetre range, and hence form a middle ground between 'detail' and 'positioning' GNSS surveying. For the purposes of these guidelines, however, they are grouped within this section.

It is important that the surveyor decides early on which type of GNSS data capture technique is most appicable to their locale and/or survey specification – national RTK network, single baseline or own base station, for example. See section 1.3, 'Survey methods'.

There may be many instances of smaller areas of detail in a mapping project where traditional survey methods are more appropriate. Such methods can be quicker and more accurate.

See **Table B**: Detail survey guidelines (p. 9).

1.2.3 Positioning guidelines

GNSS positioning frequently uses a single receiver, possibly receiving real-time DGNSS corrections or logging data for later post-processing, and is different to control and detail surveying. As a result, the accuracy for positioning is generally at the level of one to a few metres, rather than at a few centimetres. This type of survey would normally be undertaken for precise navigation or for surveying features at the metre level to input into a CAD package or geographic information system (GIS).

See **Table C**: Positioning guidelines (p. 10).

1.3 Survey methods

GNSS survey techniques can be separated into the following three methods: static surveys, dynamic surveys and real-time dynamic surveys. A full explanation of the theory behind the methods is included in Part 2, section 4, while recommended best practice field and office procedures are discussed in Part 2, section 7. In **Tables D1 to D3** (pp. 11–14), the methods are tabulated, together with their recommended applications and the results achievable. The values suggested for precision, occupation time and baseline length are those widely accepted, given a minimum of six satellites, a GDOP of three or less and normal ionospheric activity. For conditions with fewer satellites, poor geometry or high ionospheric activity, occupation times should be doubled or even increased three times.

The likely precision of each GNSS survey method is stated. However, precision is not the same as accuracy. Precision is the ability to repeat a measurement and get the same answer. Accuracy is a measure of how close the result is to the true dimension. The precision given in the tables is of the baseline components in the GNSS co-ordinate system at one sigma (σ). (This is rarely the final co-ordinate system for the survey.) One of the main sources of error in a GNSS survey is the transformation process. However, if these best practice guidelines are followed, such errors will be minimised. If this is the case, the values stated for precision will reflect those achievable for final co-ordinate system accuracy.

The use of single-frequency GNSS receivers was prevalent in the late 1980s and early 1990s. Although best practice dicates that surveyors should try to use dual-frequency receivers if possible, in some cases and with some success, single-frequency (L1) code and phase receivers are more than suitable for some detail surveys. The actual names of the different GNSS survey methods vary between the different GNSS surveying equipment manufacturers, in academia and different textbooks.

Tables D1 to D3 cover some of the various terms (pp. 11–14).

Table A: Control survey guidelines

Guideline	Explanation	Pt. 2 ref.
All surveys use source control; it is best practice to use at least 4 control stations.	This may be from Continually Operating GNSS stations (COGRs), typically provided by the national mapping agency or the International GNSS Service (IGS). Another option is for the surveyor to establish their own source control, positioning relative to COGRs or their own base stations. Alternatively, the Precise Point Positioning (PPP) technique could be used.	4.2, 7.2
Control to transform from the GNSS co-ordinate system to map projection or survey grid.	GNSS surveys are firstly observed and computed in the GNSS co-ordinate system and then transformed onto a local map projection or grid system. To do this we need to know the transformation parameters from GNSS co-ordinate system to map projection system, or include existing survey control stations with known map projection co-ordinates and heights in the GNSS survey programme.	6.3
Use stable survey markers.	When measuring with GNSS it is possible to achieve highly accurate measurements over considerable distances, hence stable monuments should be used. The type of marker recommended for control points is detailed in Annexe A of the RICS document Surveys of Land, Buildings and Utility Services at Scales of 1:500 and Larger, and can be found in other specification documents.	7.2.1
Choose control station locations where there is a good view of the sky.	It is imperative that survey control points are located where there is a good view of the sky, with no obstructions above a recommended 15 degrees elevation from the horizontal. However, in built-up areas this is sometimes not possible and the reliability of results could be adversely affected. As these control points will determine the overall accuracy of the project, the best possible locations should be selected.	5.2 5.3.4 7.3.1
Use a static or rapid static GNSS baseline survey method.	The control survey should be undertaken using ‘static’ or ‘rapid static’ methods (although network RTK may give the required accuracy under ideal conditions). The amount of data required using these procedures (observing-time) can be well defined, and hence the logistics of project planning is relatively easy. Control is needed at all scales of survey; from networks defining global reference frames, through state systems to local control for a topographic survey.	4.2
Use the precise or broadcast ephemeris according to accuracy required.	For high-precision projects it is recommended that the precise ephemeris is used. This differs from the broadcast ephemeris which is used in standard survey processing. Doing so will remove the errors associated with the broadcast ephemeris, and result in higher-precision co-ordinates for the control survey. Survey software should be checked to ensure it supports import and use of the precise ephemeris.	4.2.1

Table B: Detail survey guidelines

Guideline	Explanation	Pt. 2 ref.
Survey detail within the control framework.	It is recommended that points of detail surveyed by GNSS are within the control framework for the project, as outlined above. It is good practice to pick up the points from the control survey as a quality control check during the detail survey.	7.2
Survey in areas where there is a good view of the sky.	The same visibility constraint exists for detail points as for control points, although the accuracy considerations which inhibit station location are not as stringent. It is recommended that the complete area of detail survey to be surveyed has a clear view of the sky. Alternative methods should be considered for areas that are very severely obscured.	5.2 5.3.4 7.3.1
Exercise extreme care when surveying in urban areas.	In urban areas GNSS may not be the best technique for undertaking detail surveys due to obstructions that interfere with GNSS signals, requiring longer occupations. There may be a requirement for some conventionally surveyed work from local control points fixed by GNSS.	5.2
Use a dynamic survey method.	For detail surveys it is recommended that a dynamic technique (see paragraph 1.3 above) should be used. This affords maximum productivity for the rapid pick up of points.	4.3 4.4
When using a base and rover configuration, use a base station at a project control point during the survey.	It is best practice when using a base and rover system for detail survey using the dynamic method to use a project control point as the base reference station.This is the best way of ensuring that survey detail is correctly positioned in the project co-ordinate system.	7.3.4
When using dynamic methods, initialise in clear open areas.	In this case it is best practice to perform the initialisation of the GNSS receiver system at a location within the survey area where there are a minimum of obstructions. When a 'loss of lock' occurs and a new initialisation is required, it is recommended that this point in the survey is noted on a booking sheet or in a log file on the receiver.	7.4.4 7.4.6
Set accuracy and GDOP masks and check values before logging point.	In real-time dynamic surveys, co-ordinate accuracy and GDOP masks can be set. Ensure these are set to the value given within the specification for the survey. It is also good practice to periodically check the displayed accuracy to ensure all logged points are within specification.	7.4.1 7.4.2
Log all raw observations in real-time surveys.	This will allow the re-computation of survey results by post-processing if unforeseen problems arise and are not identified during the real-time survey. This can be of extreme benefit if observation errors, antenna height errors, transformation errors or communication/data malfunction occur during the survey. This data should also be archived and can be submitted to the client if requested.	7.4

Table C: Positioning guidelines

Guideline	Explanation	Pt. 2 ref.
Use a national DGNSS reference station for positioning.	Many countries provide both real-time base stations and/or data from base stations which can be post-processed. If the data or the real-time corrections are available for a positioning survey, it is best practice to use these, as the base stations are already positioned accurately in the ITRS89 co-ordinate system.	7.3.2
Use an accurate ITRS89 co-ordinate when using your own DGNSS reference station.	If a national differential GNSS (DGNSS) reference station is not available, then a suitable base station should be established for the project. It is best practice to survey this point and to obtain a sub-metre ITRS89 position, preferably from a GNSS control survey. This will ensure that co-ordinates generated from the survey will be precise in ITRS89 and can be used with data from other surveys.	7.3.5
Use real-time systems for most asset-capture applications.	It is best practice to use a real-time system for data capture in positioning surveys. This allows the operator to ensure that sufficient data has been captured to the required precision. It also removes the need for costly post-processing of data.	4.4.2
Do not move the captured data to fit the map.	When capturing features or assets for a geographical information system (GIS), these are usually displayed with a background map. It is best practice not to move the features to the correct position on the map, as in some cases the mapping may be in error. If such mapping is later updated and loaded to the GIS, the features will then be shown in the correct position.	4.4.2
Position some of the map features in asset surveys.	When capturing features or assets that will be presented on a map background, survey some of the actual map features such as road junctions, boundaries and other well-defined features. These can then show up in the final data as check points to assess the map accuracy.	4.4.2
For accuracy requirements of around 5–10m, use a stand-alone GNSS receiver.	As of May 2000, selective availability (S/A), the intentional degradation of the C/A code, on GPS, was set to zero, but it is technically possible for the US authorities to turn it back on again. When set to zero this allows stand-alone GNSS receivers working on the C/A code to obtain positions with an accuracy of around 5–10m. For asset data capture however, a surveying rather than stand-alone navigation receiver should be used.	4.4.2
High-quality ionospheric correction methods.	Satellite-based augmentation systems (SBAS) such as EGNOS (European Geostationary Navigation Overlay Service), MSAS (Multi-Functional Satellite Augmentation System) and WAAS (Wide Area Augmentation System) are satellite-based differential GNSS system (DGPS). The major potential inaccuracy within current GNSS surveying is related to ionospheric corrections; the geostationary SBAS create another ‘layer’ of receiver data that users can utilise for higher accuracy survey solutions.	4.4.2

Table D1: Survey methods – static surveys

Survey method	Common terms used
High-Precision STATIC	Static Precise Point Positioning
Medium-Precision STATIC	Fast Static Rapid Static
Low-Precision STATIC	Single Point Positioning (SPP) Navigation solution
High-Precision DYNAMIC	Kinematic Survey On-The-Fly (OTF) Kinematic Post-processed Kinematic
Medium/Low-Precision DYNAMIC	Code positioning Post-processed DGNSS Phase smooth code positioning ‘Degraded’ dual-frequency solution
High-Precision DYNAMIC real-time	Real Time Kinematic (RTK) OTF Kinematic Kinematic on-the-fly Kinematic, static initialisation Long-range RTK (LRRTK) Network RTK
Medium/Low-Precision DYNAMIC real-time	Differential GNSS (DGNSS) Precise navigation Real-time code/phase L1 solutions Real-time ‘degraded’ L1/L2 solutions

Table D2: Survey methods – dynamic surveys

Survey method	Typical recommended application	Precision, baseline length and suggested occupation time
High-Precision STATIC (5–10mm)[a]	National/international networks and reference frame survey Geodetic surveys to establish transformation parameters Crustal/tectonic plate monitoring surveys Land surveying, high-order control surveys Civil engineering, high-order control stations Photogrammetry, high-order ground control Remote sensing, high-order ground control Deformation studies, sea-level and tidal monitoring Atmospheric monitoring studies	Dual-frequency receivers H 5mm + 1ppm V 10mm + 1ppm B 20km for at least 1 hour 30km for at least 2 hours 50km for at least 4 hours 100km for at least 6 hours
Medium-Precision STATIC (10–60mm)	Land surveying, low-order control surveys Photogrammetry, photo control points Civil engineering low-order control High-order topographical profiles DGNSS or kinematic GNSS reference station positioning Land surveying, high-order detailing and positioning	Dual-frequency receivers H 10mm + 1ppm V 20mm + 1ppm B 20km for 20 minutes 30km for 40 minutes 40km for 60 minutes (network RTK using at least 2 sets of 3-minute observations separated by at least 20 minutes can give H=10–20 mm and V= 15–30 mm)
Low-Precision STATIC (0.1–10m)	Temporary DGNSS reference for monitor station positioning Asset positioning, at the 3m level Absolute WGS 84 determination	Autonomous receiver H 10m for 10 minutes 3m for 3 hours 0.3m for 3 days+ V twice value for H
High-Precision DYNAMIC	Cadastral surveys Land seismic Topographic mapping Structural monitoring Civil engineering, volumetric survey, area surveys Photogrammetry, camera positioning and photo control	Dual-frequency receivers H 10mm + 2ppm V 20mm + 2ppm B (after initialisation period) 1km for 5 seconds

Table D2: Survey methods – dynamic surveys (cont.)

Survey method	Typical recommended application	Precision, baseline length and suggested occupation time
(15–50mm)	Land surveying, high-order detailing and positioning GIS, high-precision asset positioning and attribute collection	15km for 1 minute
Medium/Low-Precision DYNAMIC (100mm–5m)	GIS, asset positioning and attribute collection Field asset management (FAM) Precise farming, yield monitoring Automated mapping/facilities management (AM/FM) Update of spatial data bases, digital mapping Land surveying, low-order detail surveys	Dual-frequency float/phase smoothed code receivers H 0.1–0.4m V 0.2–0.8m B 20km for 1–15 minute(s) Single-frequency receivers H 1–5m V 2–7m B 100km for 1 minute
High-Precision DYNAMIC real-time (20–80mm)	Land survey, real-time topographic detailing and profiling Land seismic, dimensional control and source positioning Civil engineering, setting out, alignment, trajectory Mining, slope stability, volumetric surveys Real-time structural load monitoring Real-time tidal monitoring Precise navigation, aircraft landing, vessels, vehicles	As for high-precision dynamic, however note that precision of Network RTK solutions is quoted relative to the network and is typically: H 10–20mm V 15–30mm B (after initialisation period) 5 seconds
Medium/Low-Precision DYNAMIC real-time (0.1–5m)	GIS, asset positioning and attribute collection Vessel positioning, hydrographic survey, offshore Fleet management and vehicle/asset tracking Precise farming, yield monitoring Public transport management Plant and stock control Military, tactical operations, vehicle tracking Personal navigation – in-car, yacht, aircraft	As for medium/low precision dynamic; however note that precision of Network RTK solutions is quoted relative to the network

Table D3: Survey methods – dynamic real-time surveys

Epoch separation	Advantages	Disadvantages
20 sec or 30 sec	Dual-frequency receivers Forgiving, tolerates cycle slips Calculates effects of ionosphere	Relatively long occupations Geodetic choke ring or ground-plane antenna is needed Advanced processing strategies required Advanced error modelling required in processing software
5 sec or 10 sec	Short occupations, very efficient No requirements for maintaining lock between points	Requires dual-frequency receivers More susceptible to GDOP problems Requires careful planning and good communication in the field Lines limited to 40km
1 sec	Low-cost receiver Only single receiver required More forgiving of cycle slips	Low level of precision only Long observation period required to obtain sub-metre positioning Need specialist processing software to get sub-metre accuracy
1 sec or 2 sec	Very short occupations Most effective data collection One person can carry out survey Dual-frequency receivers – loss of lock does not cause problems Logging of QC information to produce vectors for network adjustment, if required	Must maintain lock to 4 SVs while moving Must initialise with 5 or more satellites Most susceptible to PDOP effects Dual-frequency receivers – requires high-end receivers and post-processing software High equipment cost Requires rigorous QC and re-visits to static control points for checks
1 sec	Low equipment cost Effective technique for GIS/asset location No real-time link required – cheaper initial equipment cost	Low level of precision Vectors not appropriate for network adjustment Cannot check accuracy values of data in field
1 sec or 2sec	As for high-precision dynamic Real-time co-ordinates are available	As for high-precision dynamic Communications link between base and rover must be maintained Lines limited to 15–20km. For Network RTK the service operates anywhere within the network where communications are available.
1 sec	As for low-precision dynamic Real-time co-ordinates are available	As for low-precision dynamic Communications link between base and rover must be maintained

2 GNSS survey documentation

2.1 Client specifications

The specification for the surveyor should be based on the appropriate document for the type of survey required. **Table E** below indicates the survey type and specification document applicable.

In addition to using these documents, where possible the following client-orientated points should be observed when considering a GNSS element to the survey work:

- use a specialist survey consultant to assist in the production of a GNSS survey specification, particularly for larger projects
- surveyors should be asked to provide specific GNSS survey procedures as part of the overall project survey procedures document. This may be a simple section in a quality plan, or for large projects a specific GNSS survey procedures document as part of the bid submission
- ensure that the surveyor's procedures are fully read and technical ability is assessed before the award of contract
- include a professional surveyor in the management of the spatial data produced from GNSS surveys.

The aim of the survey specification should be to set out the criteria required for the performance of the survey and to set tolerances necessary to achieve the final results. It is most important under normal circumstances that the specification document does not instruct how the survey should be performed. A well-written specification should allow the surveyor ample scope to state his preferred GNSS methods, field procedures, equipment and reporting, all within the criteria set out. The guideline checklist will assist in writing a good GNSS section to the specification. A sample specification is given in Appendix D.

It cannot be stressed too strongly that a poorly written specification may cause the surveyor to misinterpret important aspects of the survey. This can lead to over- or under-quotation, and poor overall survey design. This will become evident in a wide range of bid prices being submitted, causing difficulty in the selection of a suitable surveyor and in obtaining value for money. The provision of a good survey specification by the client is essential.

Table E: Survey types

Survey type	RICS document reference
Land surveys at 1:500 or larger	Surveys of Land, Buildings and Utility services at scales of 1:500 and larger: Client Specification Guidelines. Superceded by Measured Surveys of Land, Buildings and Utilities (2010)
Large scale aerial mapping	Vertical Aerial Photography and Derived Digital Imagery: Client Specification Guidelines (5th edn), 2010
Small scale aerial mapping	Specification for Mapping at Scales between 1:1000 and 1:10000 (out of print but available online from RICS Library)
All types of land survey	Terms and Conditions of Contract for Land Surveying Services (3rd edn), 2009

2.2 Surveyor's procedures

The survey procedures should reflect the requirements of the client specification together with the proposed GNSS methodology for undertaking the work. The general guideline is that the GNSS survey should be conducted in a manner such that the client may ascertain that the surveying task has been achieved to the required specification. Thus when providing GNSS survey procedures the surveyor should work on the premise of:

> ' . . .this is what we think you require for the survey, and this is how we are going to undertake it and demonstrate we have achieved the desired results…'

It is recommended the surveyor should document the survey procedures to be carried out and that the checklist for surveyor procedures contained in this document is read and understood. It can be used in conjunction with the client specification to write a specific GNSS procedures part of any bid submission. A sample GNSS survey procedures section is given in Appendix E.

3 GNSS survey operations

3.1 Planning

After the tender process and award of contract for the survey, the guidelines listed in **Table F** should be used in the planning stage of a GNSS survey. Any issues, problems or questions that arise can then be resolved before the survey commences.

See **Table F** (p. 18).

3.2 Fieldwork and observations

After planning of the survey, the guidelines listed in **Table G** should be followed during execution of the fieldwork. These guidelines and explanations are a summary of best practice. A full explanation and more detailed coverage is given in Part 2.

See **Table G** (p. 19).

3.3 Data processing

Table H sets out guidelines for the processing of GNSS survey data and is a summary of section 7.5 in Part 2.

3.4 Co-ordinate systems

The selection of an appropriate co-ordinate system and reference control point will be aided by the guidelines listed in **Table I**. These are applicable for use of differing co-ordinate systems in GNSS surveys. The guidelines in **Table I** (p. 21) summarise section 6 in Part 2.

3.5 Reporting

Table J (pp. 22–23) sets out guidelines to be used when producing the report for a survey which has included an element of GNSS measurement.

3.6 Essential considerations for GNSS surveys

It is recommended that surveyors are appropriately trained and experienced in recognising the difficulties involved in GNSS surveys. When the requirements of a client are assessed, it is important that any difficulties unforeseen by the client are communicated to them. In extreme cases, the specification for the GNSS part of the survey may have to be altered to allow for these difficulties. Typical difficulties include:

- atmospheric refraction – ionospheric and tropospheric problems
- multipath
- interference.

Guidelines to overcoming these issues are considered in **Tables K1 to K4** (pp. 24–27).

Table F: Planning

Guideline	Explanation	Pt. 2 ref.
Ensure the client specification is read and understood.	This will ensure that all requirements such as accuracy and any other specific issues that relate to logistics are assessed. Any changes to survey design can also be incorporated in the survey planning at this stage.	7.1
When designing a control network, plan for closed baseline loops.	This allows network closures to be computed for the survey. The GNSS receiver set-ups and antenna heights for the survey can be checked by calculating closures around the closed loops. It is also important to re-occupy the main control points to reduce any possible antenna height errors. Incorrect baseline solutions due to multipath or other environmental considerations will also be highlighted.	7.2
Plan to observe independent baselines in the network.	If three or more receivers are used in the survey, the independent baselines should be observed to remove trivial lines in the survey. For a three-receiver set-up there will be two independent baselines per session. This removes the possibility of highly correlated observations being present in the network adjustment.	7.2 7.3
Plan to over-determine the network design.	Ensure that the network design is over-determined so that any baselines which do not process, or are too noisy, can be deleted. This will ensure there is sufficient redundancy in the network for the final adjustment. It will also reduce the likelihood of needing a return to site.	7.3
Make a contingency plan for the fieldwork.	By their very nature, GNSS observations for control involve the receivers being at sites remote from each other. This, coupled with the complex nature of the equipment, communications and logistics can lead to unforeseen problems during the survey. It is wise to make a contingency or back-up plan, especially with regard to the travelling time between points and unforeseen access problems that may occur.	7.1
Check all equipment prior to mobilisation to site.	Due to the many constituent parts of GNSS receiver systems, especially real-time kinematic systems: batteries, antennas, receivers, radios, data cards or loggers, associated cables and sundries, it is good practice to check all equipment prior to mobilisation.	
Order/check fundamental control station data.	It is good practice to check that the co-ordinates or data for the fundamental control stations are available. It is also recommended that back-up control is selected, as passive or fixed ground stations may have been destroyed.	7.2

Table G: Fieldwork and observations

Guideline	Explanation	Pt. 2 ref.
Use a booking sheet to log the survey.	This allows checks of whether antenna heights measured are true vertical or slope distance, for example. It is also a valuable quality control document to log information such as weather conditions.	7.3.3
Take a plot of expected satellite coverage.	Most manufacturers of GNSS survey equipment provide a software programme to calculate future satellite visibility. The location, time of survey and a recent almanac should be entered to the software. A plot of the expected coverage, number of satellites in view and GDOP can then be made and taken to site.	7.2 7.3.1 7.3.3
When performing repeat surveys, use the same co-ordinate values.	If surveys are repeated over time on a particular site, it is best practice to use the same co-ordinates for the fixed control and the same transformation parameters. This will help minimise variations, for example, when undertaking monitoring surveys.	6.3
Do not mix receiver and antenna types.	It is best practice to use the antenna which is designed for the receiver model, and to use if possible the same receiver/antenna combination at both the base and rover locations. Mixing should be avoided whenever possible but otherwise care should be taken. Compatibility between different firmware versions should be checked when using a mixture of receiver types in a survey.	5.3.2 5.3.3
Re-measure the base station antenna height at the end of the survey.	It is important to check for settlement of the base station during a long day's operation. This is especially important when base stations are left unattended for the day whilst survey operations proceed. It is also important in high-precision surveys and serves as a secondary check on antenna height measurement.	7.3.3
Pick up a known point after loss of lock.	In real-time detail surveys, after a loss of lock has occurred it is good practice to pick up a previously surveyed point. This can be coded as a detail or check point to ensure the correct initialisation has occurred.	7.4
Occupy another control point with known co-ordinates.	Especially when performing real-time surveys, it is good practice to survey a known control point before the survey begins. This is to ensure displayed co-ordinates are correct and is a quality control check.	7.4
Use traditional survey methods where appropriate.	The use of total station or EDM distances, horizontal and vertical angles and spirit levelling measurements should all be included in a network adjustment when appropriate.	7.2.1
Download data daily and load to processing software.	It is recommended that survey data is downloaded daily from GNSS instruments, or data loggers. This data can then be pre-loaded or pre-processed in the software to ensure all points are captured. These initial results should then be deleted and the raw data backed-up.	7.5
Recharge all batteries overnight.	Power requirements can be an important issue in GNSS surveys. Daily power loads can vary, especially when mixing static and real-time survey methods.	7.1

Table H: Data processing

Guideline	Explanation	Pt. 2 ref.
Check antenna heights twice before baseline processing.	The antenna height is one of the key factors to getting correct results for the survey. It should be checked against the booking sheet value as data is loaded, and again before processing. It is good practice to check the phase centre offsets of the antennas at this time.	App. E.2
Use the manufacturer's defaults for processing parameters.	Working within the guidelines given in this document for baseline observation times and using the manufacturer's default baseline processing parameters should result in good quality baseline solutions. It is recommended that changes to the default processing parameters are only carried out by experienced personnel; especially those changes which relate to ionospheric or tropospheric modelling.	7.5
Process fundamental control first when using long baselines to tie to national networks.	In general, design the connection of any local survey network to a national network separately. It is best practice to fix the primary control stations on site before processing the rest of the network. This follows the basic survey premise of working from the whole to the part, as outlined in section 1.1. In particular it will ensure any problems with national control co-ordinates are found at the outset and that the complex situation of combining very long baselines with short lines in a network adjustment are avoided.	7.5
Compute, print out, evaluate and confirm network closures.	The closures for a GNSS network are the first indicator that the survey is proceeding correctly and that errors have been minimised. Errors due to incorrectly estimated baseline solutions and antenna height measurements will be highlighted in the network closures so long as multiple occupations have taken place. Where baselines are observed to fix a single point from source control, the co-ordinate recovery technique should be used to demonstrate the quality of the observations.	7.5 7.5.5
Re-observe any problem baselines.	In general if incorrect baseline solutions appear in the computation of network closures, or fail processing with the default processing parameters, they should be investigated within the processing software, following the manufacturer recommendations for identifying baseline problems. If they still fail then they should be re-observed. This is because the data is likely to contain errors, perhaps due to environmental factors.	5.1 7.5
Only allow into the network adjustment closures which have passed the specification.	Any residual network closures will propagate directly into the network adjustment. Final network closures must be within the overall specification for the survey and marginal closures may need re-observation.	7.5
Ensure that the logged VCV data from real-time data is used in network adjustment.	If the survey includes a real-time component, it is good practice to store the variance-covariance (VCV) data with the positions and baselines observed. This will allow the later computation of a network adjustment, should it be required.	7.5

Table I: Co-ordinate systems

Guideline	Explanation	Pt. 2 ref.
Use good current national control points for surveys on the national co-ordinate system.	When performing a survey in a national co-ordinate system, it is essential to obtain at least two fixed points with co-ordinates in the national system. Best practice is to obtain three or more points in the national system which will allow a full check on the accuracy of the survey in the national system. A full discussion on the use and concerns of national co-ordinate systems with GNSS surveys is explained in Part 2.	6.3.5 7.2.3
Use a good single point position (SPP) for the reference station in local grid surveys.	When using GNSS for small control or detail surveys on an arbitrary local grid, the co-ordinate for the reference station should be accurate to about 10m. This can be achieved by using a single point position of a few minutes' duration.	6.3.5
For small local grid surveys, use the manufacturer's recommended local grid transformation.	As many real-time surveys are performed in small (less than 2km) areas, most GNSS manufacturers provide a simple best-fit transformation from ITRS89 to a local grid. Use this procedure, but ensure the survey is well within the area defined by the control points.	6.3.5
Use a rigorous transformation wherever possible to compute national co-ordinates directly from ITRS89 co-ordinates.	This will allow re-computation of data and co-ordinates from one system to another. This is good practice, as any errors due to transformations can be eliminated and co-ordinates can be returned to the ITRS89 system. If co-ordinates are required in a national system, use the best possible transformation available at the time of the survey.	6.2 6.3
Keep a back-up copy of all surveys in the ITRS89 co-ordinate system.	Should it be found that an error in the transformation process has taken place, this will allow the re-computation of the survey into any other co-ordinate system.	6.3.5
Follow the co-ordinate system guidelines for large engineering projects.	For larger GNSS networks (greater than 15–20km or so), use a final co-ordinate system appropriate to the project. North–south projects can use a customised Transverse Mercator projection. East–west projects can use a customised Lambert Conformal Conic projection, and other orientations can use a customised Oblique Mercator projection. If national co-ordinates are also required, compute these separately, directly from the ITRS89 co-ordinates.	6.1.5 6.3.3

Table 3.5: Reporting

Guideline	Explanation	Pt. 2 ref.
Produce a survey report that is proportional to the quantity and quality of work.	It is likely that a general survey report will form part of the products for the client. It should be of a high standard, the basic content of a typical report being covered in detail in Part 2. The basic format of a traditional survey report should be followed. This will allow the reader to understand the methods used, the results obtained and the accuracy of co-ordinates produced.	7.5
Archive hard copy of field records, baseline solutions, closures, network adjustment results and co-ordinates with precision values.	Should there be any requirement to demonstrate the precision of final co-ordinates, listings provide a definitive audit trail from the observations to the final co-ordinates and their precision in the final co-ordinate system. Hard copy of the computed baseline solutions, any optical observations used, the network closures and final constrained network adjustment and transformation parameters should be included in the bound copy of the report. It is also good practice to include a network diagram showing the geometry of the control framework. The information should be kept for a period of time in accordance with the surveyor's QA procedures.	7.5
State the co-ordinate system and transformation parameters used for the survey.	To prevent any misunderstandings or any incorrect assumptions by the client, the actual system of the final co-ordinates should be stated. The parameters and local system origin used to obtain the final system co-ordinates should be written in the report. It is also recommended that the surveyor explains how the co-ordinates have been calculated; for example, using a particular software package, or using a spreadsheet. It is especially important to record which transformation was used so that the transformation quality and history is known and the original GNSS co-ordinates can be backward-computed if required. (An extensive global collection of transformation parameters and reference frameworks can be found at www.epsg.org/Geodetic.html). This will then allow other surveyors or engineers to check the work and ensure consistency if the survey is extended in the future.	7.5
For control surveys, include a station description sheet and sketch.	It is good practice to include a description sheet for the permanent control stations which are established as part of the GNSS survey. This enables the station to be found and used in future projects. Photographs can be included.	
Back up and archive the survey project from the processing computer.	It is good practice to archive the GNSS observations, processed baselines, closures, adjustments and all associated software files from the project. This should be done in addition to the archiving of all booking sheets and hardcopy print-out from the project. Future-proofing of the digital archive should also be considered, for example one copy of the results could be kept in a plain text format.	7.5

Table J: Reporting (cont.)

Guideline	Explanation	Pt. 2 ref.
Include the makes of hardware and software; also include the versions of firmware and software in the report.	In the event of a manufacturer subsequently determining an error or problem with hardware components and firmware or software versions, this will then allow surveys that have been completed with that equipment or software to be identified. If necessary, repeat surveys can be carried out or back-up data re-processed to obtain the correct survey information. Although these problems were most likely in the development stages of GNSS, it is still best practice to include this information.	7.5

Table K1: Atmospheric refraction – ionosphere and troposphere problems

Consideration	Guideline	Pt. Pt 2 ref.
Ionosphere causes range errors to GNSS satellites. Use dual-frequency data to improve noisy ionospheric data.	Baselines <20km may not be affected due to differencing process. Baselines >20km should use dual-frequency data and processed to be ionospheric-free solutions.	5.1
Tropospheric delay causes range errors to satellites.	Use a minimum elevation angle of 15 degrees in processing. Use a standard model to estimate the tropospheric delay in the processing software. Be aware that long baselines cannot be improved using dual-frequency receivers, and that the height component is most affected by this error. Observing satellites with a good separation in azimuth and good GDOP should mitigate some of its effects.	5.1

Table K2: Multipath

Consideration	Guideline	Pt. 2 ref.
Buildings and other structures cause reflection of GNSS signals.	Locate control station positions away from structures, especially those with a sloping roof or other angled surface. Avoid areas and locations which may be susceptible to variable multipath, for example near road traffic. Use another survey method (e.g. total station) to get a position in a critical location.	5.2
Low elevation satellites, signal-to-noise ratios, receiver and antenna types all contribute to multipath.	Be aware that in locations where multipath is present, it is good practice to carry out a standard test to verify the level of multipath. In locations where multipath is present and unavoidable, observe over as long a time as possible. Twice the recommended time given in section 1.3 above is a good guideline.	5.2

Table K3: Interference

Consideration	Guideline	Pt. 2 ref.
Jamming of GNSS signals can occur from other radio signal sources.	Avoid locations where radio interference is present. Test during the planning phase at critical points. Avoid locations where radio interference might be present, e.g. near radio and television masts.	5.3.1
Electrical noise from machinery and electronics can cause problems to GNSS signals.	Avoid locations where interference from machinery or electronics might be present. Design and observe control networks with sufficient redundancy to allow for the loss of baselines due to unexpected interference.	5.3.1

Table K4: Other matters

Consideration	Guideline	Pt. 2 ref.
GNSS surveying is a complex survey activity and appropriately trained staff should be used for both fieldwork and survey processing.	Surveyors should be formally trained with the particular equipment they are using. It is best practice to use surveyors who have had GNSS theory included as a part of their formal survey training and education and have had some years' experience in the use of GNSS in land surveying. It is recommended that evidence of competency be available if requested by a client.	
Mixing antenna and equipment types.	Best practice is to use the same generic models of GNSS equipment throughout a survey. It is recommended not to mix antennas, receiver types or different firmware versions. If unavoidable, be aware that different antenna types have different phase centre variations and ensure the correct values for the phase centres are used in the processing. GLONASS observations experience various hardware delays for each transmitting satellite (or each frequency) named 'interchannel biases'. The frequency-specific hardware biases complicate resolution of double-difference phase ambiguity. Antenna phase biases depend on the receiver and antenna used. If different receivers/antennas are being used at the base and rover, the base station (or Network RTK service) should be transmitting what manufacturer type it is – the rover will then be able to take this bias into account. Ocean tide loading (OTL) is the time-varying displacement of the earth's surface due to the weight of the ocean tides. In the British Isles it can reach ± 60 mm in height and ± 20 mm in plan in the South-West Peninsula and Western Isles, although it is typically less than half of this magnitude. Instantaneous differences in OTL between a rover and base station can cause errors in the measured co-ordinates.	5.3.2 5.3.3
Maintaining data radio and other communication links	Be aware that in countries where RTK radio link frequencies are in a public access band, congestion of the radio band may occur. It is good practice to take a radio scanner to site to check proposed frequencies before beginning the survey. It is also recommended that surveyors check the frequencies and transmission power proposed, to ensure they are within the radio licensing laws of the country. It is also good practice to allow an interval of time to pass (a self-checking window) when re-acquiring a radio signal. This will allow initialisation to be checked at the rover receiver, as a loss of lock may have occurred at base.	
Foliage and vegetation cover.	Be aware that under foliage, particularly when leaves have a high moisture content, the GNSS signal to noise ratio is affected such that complete loss of lock can occur. Locate control stations as far away from trees as possible.	5.3.4

Part 2 – Technical commentary

4 GNSS survey methods

This section deals with the technical aspects of survey methods applicable to GNSS use, expanding on the generalised descriptions and guidelines contained in Part 1 of the guidelines. A good understanding of its content should be considered essential for senior surveying staff involved with the provision of GNSS-related surveying services. For others it will provide invaluable background information to enhance their abilities to specify or carry out the work.

4.1 General principles

This first section simply describes the process of GNSS positioning used in surveying. There are two methods by which station positions in the GNSS reference frame can be derived: relative positioning and point positioning.

In relative positioning, two or more GNSS receivers receive signals simultaneously from the same set of satellites. These observations are then processed in one of two ways. In the first way, the components of the baseline vectors between observing stations (station co-ordinate differences DX, DY, DZ) are determined. Once the co-ordinates for one or more (base) stations are known, new (rover) stations can be determined with an accuracy relative to the known co-ordinates. The other processing technique uses a single GPS receiver located at a known point (base station) which compares observed satellite ranges with known ranges. These corrections are then made available to other receivers in the vicinity (DGPS).

Relative positioning can only be used in situations where there are source control stations with known co-ordinates. Many countries have a network of continuously operating GNSS receivers (COGRs) which may be used as source control. The COGRs are fixed over points of known co-ordinates in a defined reference frame, and typically record data at 15- or 30-second intervals. The data is stored in Receiver INdependent EXchange (RINEX) format on webservers, enabling third parties to download data for the stations and time periods required.

In some countries, one-second data from the same network COGRs are used as the basis for a network RTK service provider to model errors affecting GNSS over the network and supply a real-time correction service to subscribers, usually via the mobile phone network.

Two of the most popular network RTK correction formats are Master Auxilliary Concept (MAC) and Virtual Reference Station (VRS). If the MAC protocol is used, the network provider transmits the co-ordinates and raw GNSS data for one COGR with modelled network correction information which the subscriber's receiver can use as source data. If the VRS protocol is used, the service provider calculates modelled GNSS data for a point very close to the subscriber's receiver, and transmits it as if this virtual data were being transmitted from a real base station.

If there is no national COGR data available, the surveyor has the choice of using data from one or more of the International GNSS Service (IGS) COGRs (see www.igscb.com) or establishing a point position fix as the source control for the survey.

In the point positioning method, data from a single station is processed to determine three-dimensional cartesian co-ordinates (X, Y, Z) referenced to the WGS 84 earth-centred reference frame (datum). The present accuracy for GNSS point position determinations ranges from 0.3m to 30m (one sigma σ), depending on the accuracy of the ephemeris and period of the observations. This is the standard method used for stand-alone navigation receivers.

4.1.1 Observation types

When using either method, the receiver processes the code that is modulated onto the signal, often plus the phase of the carrier signal. Signals can currently (2009) be received from GPS and GLONASS satellites, but in the course of the next few years a new signal will be introduced to the GPS constellation and signals from Galileo satellites will become available. The Chinese GNSS system Compass is also envisaged to join the global postioning constellation in the next decade.

Although these observables have different characteristics, they are both functions of the instantaneous ranges between satellite and ground stations and their time derivatives. The most precise measurement type is the carrier phase. Linear combinations of the code and carrier phase observables are all used in the process of ambiguity resolution, when relative positioning is being undertaken. The variety of combinations used depends primarily on the manufacturer's preferred processing methodology. Most software packages available today offer code/phase combinations for the rapid determination of ambiguities either in rapid-static or fast ambiguity resolution mode.

4.1.2 Error sources

The major factors, or error sources, affecting precision of position determinations by GNSS can be grouped into the following categories:

- accuracy of the satellite positions (ephemeris)
- receiver timing bias, or tracking errors
- ability to model atmosphere (ionospheric and tropospheric) refraction
- procedural errors in the field
- co-ordinate transformation errors
- multipath.

4.1.3 Differing survey methods

The surveying methods that use either relative positioning or point positioning can be suitably divided into static survey methods and dynamic survey methods. The static methods involve the GNSS receivers remaining stationary during observations. However, when using dynamic methods the antennas move and stop occasionally for short periods over a survey point, logging sufficient data to fix the co-ordinates of the point.

There are numerous combinations of GNSS survey methods for achieving a specification. Each will need to be considered with the following factors in mind:

- accuracy
- availability of control
- equipment constraints
- personnel and logistic limitations
- cost
- quality criteria.

Tables D1 to D3 (pp. 11–14) give the precision, timing and implications of each method and should be referred to when deciding upon possible methods for a given application.

There are also 'single receiver' systems that can be used for surveying, which may give results accurate to a few centimetres. These are commonly known as network RTK systems in which a third party operates a network of COGRs covering a large area (usually national). The base station data is used to model errors in the network and supply a correction service to subscribers in real time. It is essential to carry out independent checks on the survey. These could include a mix of GNSS observation techniques (e.g. static and network RTK), checking against existing surveyed points, using detail survey observations to gross error-check the control and, where height is important, spirit levelling between control stations.

When using these systems, much of the control of the survey is taken away from the surveyor. It is essential that a high level of quality control and as many independent checks as possible are applied when using these systems for surveying (see section 7). Specifically, static control networks should always be used to provide an overall geometric framework for a project. The co-ordinates of these stations should be fixed initially so that independent checks can be carried out by measuring these points during the survey.

4.2 Static surveys

In a static GNSS survey, the antennas and receivers remain fixed during the period of observation. The levels of precision attainable and observation times when using the different static methods are listed in **Tables D1 to D3**. In general, a millimetre error in height is likely to be more important to the customer than a millimetre error in plan, but the precision of GNSS is worse in height than in plan – usually by a factor of two. This means that, frequently, GNSS surveys are operating close to the limit of the technology when surveying height. British surveyors should refer to the RICS Geo client guide *Virtually level – a guide to the change from traditional benchmark levelling to GNSS heighting,* downloadable from www.rics.org/mappp.

Where GNSS observations are to be used solely to fix plan position, the site chosen for the control station need not be perfect; however, when the accuracy of the height component is required to be better than 40mm, site selection is more important. In this case the reliability of the results will be adversely affected by trees blocking the signals and by multipath from buildings and reflective objects. It is best practice to select sites for GNSS control observations that have a completely clear sky view above 10° elevation and no objects such as buildings that might cause multipath (alternatively, Virtual RINEX data can be used, which replaces the need to set up a base station if the area is within a COGR network). In addition, the survey stations should be connected by closed loop spirit levelling, which should be moved up or down to best fit the GNSS height observations, rather than adjusted to fit the GNSS-observed heights.

In this section, static surveys are grouped in descending levels of precision.

4.2.1 High-precision static

Dual-frequency static (for lines of less than 100km) methods are most suitable for control surveys and afford the highest precision (sub-centimetre) achievable with GNSS. It requires the simultaneous observation at two or more stations of GNSS data from four or more common satellites. Carrier phase and code measurements are made on all available frequencies. A baseline vector is computed after the observations have been logged, using a differencing technique. This is not explained in detail in this document. Full details can be found within the books listed in Appendix C.

The baseline computation is a series of processing steps. Triple differencing is often used, firstly to determine and correct cycle slips in the data. The baseline estimation then proceeds using a double difference of the phase observables. In modern processing methods highly advanced statistical testing is carried out to determine the best candidate within a search area, for integer ambiguity determination. A series of solutions can be determined using combinations of the phase obervables such as 'wide lane' or 'narrow lane'. These are often used as a step to confirming the final solution, which is either 'iono free fixed' or 'L1 fixed', according to baseline length.

A successful outcome from each of these processing steps is most likely when:

- there is a large amount of good quality data
- the antennas remain stationary during the observations
- there is a significant geometry change in the satellite constellation.

As these conditions all exist in the high-precision static method, the best results are achieved. The high volume of data is used to not only solve for the integer ambiguity as mentioned above, but also to solve for other unknowns in the mathematical process of computing the baseline.

In addition, other errors such as the delays caused by the atmospheric refraction can be solved by the software. In essence, high-precision surveys require the removal of as many system errors as possible. This includes the use of the precise ephemeris, as it removes the orbital errors which are present in the broadcast ephemeris. The actual ephemeris is available in several forms (rapid, ultra-rapid, precise) from various sites on the internet and is generated from earth tracking stations which precisely measure the satellite positions. It is usually available for download a few days after the survey data has been logged. It is important to ensure that the make of the processing software and the version being used is capable of importing a precise ephemeris and using it correctly. When computing baselines of longer than about 80km, 'scientific' software which incorporates algorithms to compute ocean tide loading and tropospheric errors should be used.

Epoch settings or 'epoch intervals' are the rate at which data is logged in the memory of the receiver. In the differencing process, to compute the baseline solution the observations from one epoch are differenced with those from the next. The interval appropriate for any particular survey depends on a variety of factors. These include the type of baseline processing software, the amount of memory available in the receiver, and the density of point data needed for the survey. In a static survey, as the antennas remain fixed, there is no need for an epoch setting of less than 15 seconds. In some cases, when long baselines are involved and noisy atmospheric conditions exist, it is best to reduce the epoch settings still further, to 20 or 30 seconds. Whatever epoch setting is selected, it is imperative that all receivers used in the survey are set to the same interval.

Historically, single-frequency static methods were also used for high precision control surveys. However, with the introduction of relatively low-cost, dual-frequency equipment, the use of single-frequency equipment in surveys is becoming less common. The main drawbacks to single-frequency surveys are the limiting baseline length of some 5 to 10km, and the need for much longer occupations to achieve the same accuracy. This is predominately due to atmospheric refraction considerations, as discussed in section 5.

4.2.2 Medium-precision static

Lower-order control surveys, typically those that require precision of about a centimetre, can be carried out using either a static technique detailed in 4.2.1, rapid static techniques or (where it is available) network RTK.

The rapid static survey method is similar to high-precision static surveys, but occupation times are reduced, depending on conditions. The key technical differences between high-precision static and medium-precision static are as follows:

- dual-frequency data must be used for the survey
- the processing software must have sophisticated processing algorithms to allow computation of the baselines
- the survey data must be virtually free of cycle slips, multipath and interference
- good satellite geometry is critical
- baselines are limited to a maximum of 40km.

These more onerous conditions are all required because a smaller amount of data is used to estimate and obtain the correct baseline solution.

The method works by using a higher epoch rate of five or ten seconds in the differencing process. This allows the same number of differences to be computed for a 20-minute observation of five-second epoch, as for a one-hour observation of 15-second epoch, assuming the same number of satellites. Thus, the mathematical solution of the baseline can be found. However, the presence of cycle slips, multipath and little change in satellite geometry, introduces noise into the solution. In the worst case, the limited data will fail statistical testing, and a fixed integer solution will not be computed by the software.

In most cases this will result in the necessary re-observation of data to compute the baseline. The use of float solution baselines and advanced processing techniques to accept marginal solutions is not recommended. In the general case the limited data allows baseline computation to an acceptable L1 or iono-free fixed solution. However, assumptions are made by the mathematical models used in the processing software and this leaves some system errors in the solution. Hence, the solutions are not as precise as in the high-precision static case.

Tests in Great Britain have shown that it is possible to obtain position to RMS 10–15mm and height to RMS 15–30 mm from network RTK observations. Where these are used to fix survey control stations, as a minimum, observations should be made using two sessions of three minutes separated by at least 20 minutes, preferably under different satellite configurations. Where used to fix the control station in height, at least two network RTK stations should be observed which should be adjusted to closed spirit levelling, as described in section 4.2. For further detail see *TSA Best Practice Guidance Notes for Network RTK Surveying in Great Britain* (see www.tsa-uk.org.uk).

4.2.3 Low-precision static

This uses the point positioning method rather than relative positioning method, as described in section 4.1. A single GNSS receiver is located at an unknown point and logs data for a period of time. The absolute maximum precision that can be obtained using this type of survey (approximately five days' logging) is about +/- 0.3m. The processing to obtain this position is a simple averaging of the satellite observations or the positions computed.

Typically known as a single-point position, or SPP, this method for obtaining absolute positions is suitable in locations where fundamental control information is of limited availability. The receiver is operating in the default point positioning mode, therefore epoch settings are typically at the GNSS system default of one second. The use of dual-frequency data slightly improves the final position solution in this method, and is discussed in section 5.1.3.

4.3 Dynamic surveys

Dynamic GNSS surveys provide the highest production rate for all the GNSS methods. Whilst rapidly generating co-ordinates, the precision obtained is not as high as by static techniques. This is because in dynamic techniques, most random measurement and GNSS system errors are absorbed in the co-ordinates. This can be contrasted with static methods, in which they are absorbed in the residuals after a network adjustment. Dynamic surveys can be post-processed or carried out in real time, with the addition of a suitable communications link.

4.3.1 High-precision dynamic

For high-precision dynamic surveys, the methods of kinematic and on-the-fly kinematic can be used. The basic technique is the same: to keep one receiver fixed at a known control station (base) whilst one or more other receiver(s) (rovers) move around the site observing the same satellites. The difference is that, in the kinematic technique, both receivers must initialise on a known baseline and then maintain lock on at least four satellites throughout the session. The on-the-fly method, however, does not require an initialisation on a known baseline. Thus, the survey can tolerate periodic loss of lock during the survey, as the 'integer ambiguity' can be determined whilst the rover is moving to the next point. Each technique results in baseline vectors from the base station to each station visited by the rover. For surveys requiring detail, or co-ordinates to be captured at an accuracy of a few centimetres, these techniques can be used. In such surveys, as the receiver at which the baseline solution is being calculated is moving, a short epoch setting is needed. Typically an epoch setting of one or two seconds is used for standard detailing for land surveys. For engineering surveys or photogrammetic camera positioning applications, epoch settings of 0.1 to 0.5 seconds are typically used.

With these rapid epoch settings, differencing techniques are used with statistical search methods to quickly compute the initialisation baseline solution from the data. In the on-the-fly technique, the most advanced baseline solution methods are used to determine the baseline initialisation and then to test it, to ensure it is the correct one.

As only one to two minutes of data are used for this initialisation process, the data must be as clear as possible from multipath and cycle slips, otherwise incorrect baseline solutions will result. Thus, when initialising on-the-fly surveys it is important to move to a location which has an open view of the sky. It is also good practice to re-occupy previously surveyed points after a new initialisation, as this proves that the new solution is the correct one.

Once the initial baseline is computed, the co-ordinates of the roving receiver are computed for each epoch. The integer ambiguity of the baseline is known from the initialisation process and thus the new baseline solution at each epoch can simply be determined from the change in the satellite observations. The changes are due to the satellite movement and the receiver movement. From the ephemeris the movement of the satellites is known, hence the movement of the receiver is solved from the mathematics in the processing software. This is why only a few seconds of data are required at each new survey point.

Network RTK service suppliers may provide a post-processing service for high-precision dynamic GNSS. This is usually used as a back-up, should the real-time service described in section 4.4.1 be unavailable. Surveyors in some areas of the world may find the free online post-processing services useful available from www.ga.gov.au/geodesy/sgc/wwwgps/

4.3.2 Medium/low-precision dynamic

For detail surveys, or asset positioning that requires sub-metre precision, post-processed differential GNSS techniques can be used. This technique uses the same general technique as the high-precision method but can be based on L1 code, dual-frequency float or phase-smoothed code solutions. The result, with sufficient logging time, can yield positioning up to the decimetre level.

As outlined in section 4.1, the post-processing method uses a base receiver to determine the groups of GNSS system errors inherent in the point positioning process. These are then used to correct the errors at the rover, which are assumed to be the same.

4.4 Real-time dynamic surveys

With the addition of a suitable communications link, all the dynamic survey types detailed above can be carried out in real time. The actual dynamic GNSS technique is the same, however, the processing software is loaded into the rover receiver and co-ordinates can be output in real time. It is critical, therefore, when using this technique, that the GNSS receivers have the correct firmware loaded for the chosen real-time method. The precision for a single baseline is the same as for post-processed survey, but higher precision adjusted co-ordinates for control surveys cannot be produced in real time using this technique. For control surveys, static or rapid static methods should be used as in the guidelines above.

4.4.1 High-precision real-time

In high-precision base and rover real-time (RTK) surveys, high-speed communications links are used to transmit the base data to the rover. It is common for manufacturers to use UHF or VHF links integrated into base and rover complete kits. These are often supplied with the base in a rugged case with a GNSS receiver, radio, modem, power supply and antenna, all cabled together ready for use with the rover in a rucksack or on a pole with antenna, power, GNSS receiver, radio, modem and cables all mounted on or inside it. Base data can also be transmitted to the rover by GSM or GPRS over a cellphone network.

Network RTK can be used for high-precision real-time surveys. With this technology, instead of having a base instrument set up over a known point and sending base data to the rover, the user subscribes to a network RTK correction service which provides the base station data (or equivalent), usually via GPRS cellphone. This only works where there is mobile phone cover, unless a radio repeater device transmits the data into the survey area from an area where there is mobile phone coverage. If there is no cover, the correction service provider usually provides data for post-processing.

If the GNSS antenna is mounted on top of a pole, the operator typically uses a hand-held or pole-mounted data logger. In other applications the rover system can be mounted on vehicles in a suitable manner. It should be noted that the orientation and inclination of the vehicle can have appreciable affects upon the resulting co-ordinates and heights. The baseline processing and epoch settings for real-time surveys are all the same as described above in section 4.3.1, and are not repeated here.

4.4.2 Medium/low-precision real-time

For surveys or positioning that require a precision of a decimetre to a few metres, real-time differential GNSS techniques can be used. These systems vary in the achievable precision. Standard systems using corrections to the pseudoranges as described above in section 4.3.2 can be used to obtain precisions of two to five metres. However, more accurate systems using real-time smoothing of the data by observations of the carrier phase will achieve a precision of between 0.4 and about one metre, according to operational considerations. Dual-frequency data techniques are also employed which obtain precision down to the one to three decimetre level.

For standard DGNSS the method is the same as that outlined above. However, there is an international standard (RTCM SC-104) for the format of the transmitted pseudorange corrections. As well as setting up your own base station, corrections can be obtained from either free-to-air or fee-based satellite, phone or radio-based services. Due to the widespread use of this technique in hydrographic surveying, detailed guidelines for the use of DGNSS have been produced by the United Kingdom Offshore Operators Association (UKOOA) (see www.imca-int.com/divisions/marine/publications/199.html).

In the carrier-smoothing method, several consecutive epoch observations are needed to obtain the system precision. This is because the differences in the measured pseudorange corrections and rate of correction are compared with the actual carrier phase differences between epochs. Thus, for this to be carried out precisely, several epochs of carrier data with no cycle slips are required. Typically one-second epochs are used for GIS asset surveys. In particular the correct solution can be checked by occupation of control points or by checking map features which can be located on background maps in loggers.

Dual-frequency techniques are also used, but unlike RTK where integer ambiguities are fixed to give few-centimetre precision, the integers are kept to float so the end precision is at the one to three decimetre level.

As with high-precision real-time surveys, network GNSS techniques can deliver corrections to the user in the field.

This concludes the general technical explanation behind the survey methods. As a full treatise on GNSS theory is not within the scope of this guidance note, this section has been vastly simplified.

5 Operational considerations

Section 3.6 of Part 1 outlines typical difficulties in GNSS surveys. These can be separated into propagation errors (due to atmospheric refraction and multipath effects), interference and other difficulties. Each of these is addressed individually in the sections below.

Propagation effects have a common feature, in that they make the apparent distances between the satellites and the receiver longer, resulting in a positional error. The differential approaches adopted in most GNSS surveying techniques, either with carrier phase or with differential pseudorange (DGNSS), tend to cancel out much of the error due to atmospheric effects. However, this is not the case with multipath, as it is predominantly dependent on the location of the receiver and the immediate surroundings.

Interference is a significant consideration when using GNSS. This may be unintentional in nature, or due to deliberate jamming. The former may be avoided to some extent by the careful location of observing sites. However, the latter cannot be allowed for by simple planning, and must be addressed at the institutional level and backed up by an efficient and reliable dissemination of information. Other difficulties are often overcome by careful planning of the survey and remembering the use of other survey techniques.

5.1 Atmospheric refraction

As microwave signals (such as the GNSS signals) pass through the earth's atmosphere, their path is bent and the signal is delayed. The bending effect is usually ignored, hence the main concern is the propagation delay. The atmosphere may be conveniently regarded as having two distinct strata, namely the ionosphere and the troposphere. The treatment of the two strata differ fundamentally, due to the nature of their effects and the ability to model these. Consequently they will be dealt with separately below.

5.1.1 Ionospheric refraction – description

The ionosphere affects GNSS code (pseudorange) and phase measurements in different ways. The code measurements are delayed (i.e. the distances are measured longer than they really are), and the phase is advanced as the signals pass through the ionosphere. The ionosphere is also a dispersive medium at radio frequencies, and the effects will vary, depending on the frequency of the signals. The other contributing factor to the variation is the free electron density within the ionosphere. This factor is governed by the activity of the sun and the level of activity of the ionosphere changes with a number of well known periodicities, including the 11-year sun spot cycle, a seasonal cycle, and a diurnal cycle. The next solar maximum is due in 2011. Magnetic storms superimpose a sizeable irregular pattern over these cycles, making the prediction of the free electron density very difficult. During a solar maximum, the vertical ionospheric error can reach up to 10m (at GNSS frequencies) during the day, reducing to between 1 to 2m at night.

The frequency dependence of the ionospheric effect allows for a relatively straightforward elimination of the effect, provided observations are made at two frequencies. The situation is not so straightforward for users of single-frequency GNSS instruments. The variability in the state of the ionosphere makes it very difficult to produce a reliable estimate of the electron density and hence eliminate the effect. Although more complex models are available, the GNSS navigation message includes a simple model developed by Klobuchar. This model is based on a simple cosine representation of the ionospheric delay, and the amplitude and period of the model are allowed to change as a function of local time and geomagnetic latitude. A constant night-time delay is adopted. This model represents something of a compromise between accuracy and computational complexity, such that the accuracy is limited to approximately 50 per cent of the total effect.

5.1.2 Ionospheric refraction – implications

Single-point positioning with GNSS, using single-frequency pseudorange measurements, relies on the direct measurement of the satellite-to-receiver range, although it should be noted that satellite geometry exerts a strong influence. Since the effect of the ionosphere is to delay the code signal, a neglected, or under-modelled, ionosphere will result in pseudoranges that are too long. Consequently, the resulting co-ordinates of the antenna will be biased away from the satellites. This generally means that the position of the receiver will have a greater error in the height component rather than the horizontal position. These errors can amount to several metres, if uncorrected. The use of two frequency code measurements would effectively eliminate this error. For relative positioning, either with code or carrier phase measurements, the differencing process tends to cancel the effects of the ionospheric delays. Provided the two receivers are reasonably close to each other (less than 20–30 km apart), it can be assumed that the signals are travelling through the same portion of the ionosphere, hence the effects on the received signals will be the same. By differencing the observations, either directly, as in GNSS processing software, or indirectly, as in DGNSS, this common error will be cancelled. As the separation between the two receivers increases, this assumption becomes less valid.

As a result, dual-frequency receivers are usually used for surveying longer baselines in order to observe the effect of the ionospheric delay on the two frequencies. This can then be solved for in the GNSS post-processing software as an unknown, hence the need for more data on long baselines.

5.1.3 Tropospheric refraction – description and implications

At radio frequencies the troposphere is a non-dispersive medium. Thus, its effect cannot be eliminated from two-frequency measurements as with ionospheric refraction. The estimation of tropospheric delay relies, instead, on the use of one of a number of models. These models generally characterise the troposphere as two components: a dry component and a wet component.

The dry term accounts for about 90 per cent of the total effect and can be accurately modelled from measurements of surface pressure alone (Hopfield, 1971). Errors do remain in these models due to the difficulty in assessing where the top of the troposphere is and horizontal gradients in the atmosphere.

The remaining contribution of the wet term is more difficult to model accurately since measurements of temperature and partial water vapour pressure at the antenna are generally not representative of the conditions along the signal path to the satellite. Partial water vapour pressure distribution within the atmosphere is extremely variable. Consequently, it is virtually impossible to model the horizontal and vertical gradients to a high degree of accuracy.

Table L below gives a general indication of the errors attributable to both wet and dry terms at various elevation angles.

Various methods are available for measuring the amount of water vapour in the atmosphere, although the expense and inconvenience of these methods mean that none is ideal from the point of view of a field user of GNSS. The usual approach for estimating the tropospheric effect is therefore to apply one of a number of empirical models. The application of these models should, in most cases, reduce the tropospheric error to a few centimetres, with the remaining uncertainty being attributable mainly to the wet component. Errors in the models become more significant at lower elevation angles, and it is common practice to restrict observations to a minimum elevation of, say 15 degrees.

Table L: Tropospheric refraction

Elevation angle (°)	Dry term (m)	Wet term (m)
90	2.3	0.2
30	4.6	0.4
15	8.9	0.8
10	13.0	1.2
5	26.0	2.3

Errors in the troposphere which are common to two receivers will cancel in the same way as the ionospheric errors for relative positioning. However, the use of dual-frequency over long baselines will not lead to any improvement. Absolute positioning errors can be up to several metres, if left uncorrected, although the application of one of the standard models should reduce the effect to the decimetre level, with errors in station height again being the most pronounced.

5.2 Multipath

Multipath in GNSS measurements is a propagation error caused by the reflection of GNSS signals en route between the transmitting satellite and the receiving antenna. Signals which have not followed the direct line of sight between the satellite and receiver interfere with the direct signals, and cause an error in the measurements. Multipath can occur at both the transmitting and receiving end of the signal, i.e. at the satellite and at the ground antenna. The magnitude of the effect can reach several metres in pseudorange measurements, and errors of this kind directly affect the accuracy of a positioning solution. Fortunately, the effect on carrier phase measurements is about two orders of magnitude less than on the code measurements. Although carrier phase may be the prime observable for surveying and geodetic applications, the pseudorange measurements are used in order to resolve the initial ambiguities of the phase measurements.

The effect of multipath is different for each satellite, and varies as the satellite moves across the sky. Since the effect is dependent on the location of the receiving antenna, multipath errors clearly cannot be eliminated by differential corrections. In fact, as multipath at a mobile receiver and multipath at a reference receiver are uncorrelated, they may consequently have an additive effect.

The factors which determine whether a particular GNSS installation is susceptible to multipath are many and varied. The location of the GNSS antenna with respect to reflective surfaces, the design of the antenna, the type of correlator in the receiver, the signal to noise ratio, and the elevation and azimuth of the satellites, all contribute.

5.2.1 Multipath – implications

If an environment is ‘unfriendly’ in terms of multipath, then the best strategy is to observe over the longest possible period of time, in an attempt to average out the effect. This has obvious implications for methods which use rapid initialisation such as medium precision static, where occupation times are typically of the order of 10 to 15 minutes, and for dynamic methods with observation durations of a few minutes at the most.

Determining the susceptibility of a location to multipath in both static and dynamic real-time GNSS survey methods is a problem which has been investigated. A critical test for static survey applications is given below, which should be used only when absolutely necessary from a commercial point of view. It is far better to observe somewhere else and transfer a co-ordinate to the required location using a traditional survey method. Antenna design is becoming increasingly advanced to cope with the effects of multipath, through the use of polarised antennas and choke rings. Furthermore, a consequence of phase-smoothing is that multipath effects are attenuated, due to the reduced effect of the multipath on the carrier phase.

5.2.2 Multipath – critical testing

Various simple tests have been proposed to identify whether or not a given installation of a receiver actually suffers from a significant amount of multipath, in either the pseudorange or carrier phase measurements. In general, it can be assumed that for an antenna site which experiences multipath in carrier phase measurements, there will also be an effect on the pseudoranges, simply because the site has reflective surfaces in the vicinity. However, the effect on pseudoranges is not exactly the same as the effect on carrier phase, and could be many times larger. One standard method of identifying carrier phase multipath is to examine residual plots on consecutive days. If trends can be seen from day to day, then one can infer that the results are not due to random effects, such as the atmosphere, but must be due to multipath.

The premise behind this method of detecting multipath is that, for a static receiver, multipath effects repeat on successive days. Since the location of any reflective surfaces, relative to the antenna, does not change, signals from a satellite at a given location in the sky will always experience the same multipath. Since the orbits of the GNSS satellites are such that each satellite will appear at the same point in the sky every 24 hours (approximately), multipath effects on each satellite will repeat daily. There is, in fact, a slight shift in the GNSS satellite constellation from one day to the next. The orbital period of a GNSS satellite is approximately two minutes short of 12 hours, with the result that a satellite will rise and set four minutes earlier each day. Consequently, the pattern of multipath effects in GNSS measurements will also advance by four minutes each day.

This test does have a number of drawbacks from an operational point of view. Since the baseline processing involves the use of the double difference carrier phase observable (involving two satellites and two receivers), it is not possible to identify which of the two satellites involved is contaminated by multipath, and more importantly, which of the two receivers is contaminated. Thus, great care would have to be exercised in locating the second antenna away from any reflective surfaces, to ensure that the test could correctly isolate multipath effects in the antenna under investigation.

5.3 Interference and other operational considerations

This section covers some of the other operational issues which cause errors in GNSS surveying, in particular interference and mixing equipment types in surveys.

5.3.1 Interference

The GNSS signals are particularly sensitive to interference from other transmissions, either as unintentional interference or from deliberate jamming. The sensitivity is due to the very low levels of the GNSS signals, so low that the resultant signals are below the ambient noise level at radio frequencies. The Standard Positioning Service (SPS) is considerably more sensitive to interference than the military Precise Positioning Service (PPS). Signals at sufficient levels to affect GNSS reception could arise from the upper harmonics of microwave links, radar, television transmitters, satellite and VHF communications and amateur radio. In addition, electrical noise from electronics and electrical machinery may also cause problems.

The problem of interference is being addressed by the receiver manufacturers, and an increased robustness to interference largely depends on a good front-end RF filter. GNSS is so susceptible to interference because the radio frequency bands used are not generally protected. The impact of interference on the receiver can be quite varied, ranging from complete loss of lock on the signals to the introduction of cycle slips into carrier phase measurements. Improvements in receiver design will not eliminate all problems and the simplest approach is to avoid sites of possible interference, particularly areas around radio and television transmitters. GNSS interference can also be very variable in nature and so it is most important to build adequate redundancy into a network to cope with losses of data due to interference.

5.3.2 Mixing equipment and antenna types

There are a number of reasons why it is not recommended to mix equipment and antenna types. Firstly, it is vital to only use antennas which have been designed specifically for the GNSS receivers proposed for the survey. The electrical characteristics and pre-amplifiers used in antennas are all different, especially between different manufacturers. Use of an antenna not designed for a particular receiver may result in poor, irregular or incorrect tracking of the GNSS signals and at worst, damage to both antenna and receiver.

The second reason is that mixing receiver types within a survey project can result in systematic height errors if the antenna phase centres are not modelled correctly. The processing software must be capable of correcting for the different antenna types. The model of antenna used on site (including the antennas at any COGRs used) must be known and the correct antenna phase model used in baseline processing. Antenna phase models must be either all relative or all absolute, and should be from the same source (e.g. NGS).

In addition, phase centre variations (section 5.3.3) may not be included in the software models. In real-time surveys, the manufacturers often use a bespoke data format for the transmission between base and rover. Thus, it is extremely unlikely that a rover unit from one manufacturer will work with the base station from another. Even if such an arrangement is claimed to work by the manufacturer, it is not recommended as best practice.

Apart from the above two reasons it may simply be found on completion of the fieldwork that data from one manufacturer's receiver will not load correctly into processing software from another manufacturer. Data may subsequently be available in RINEX format, but manufacturer-specific information can be lost in conversion to this format. Advanced processing techniques may be needed for RINEX datasets, as specialist knowledge can be needed to reduce the possibilities for error.

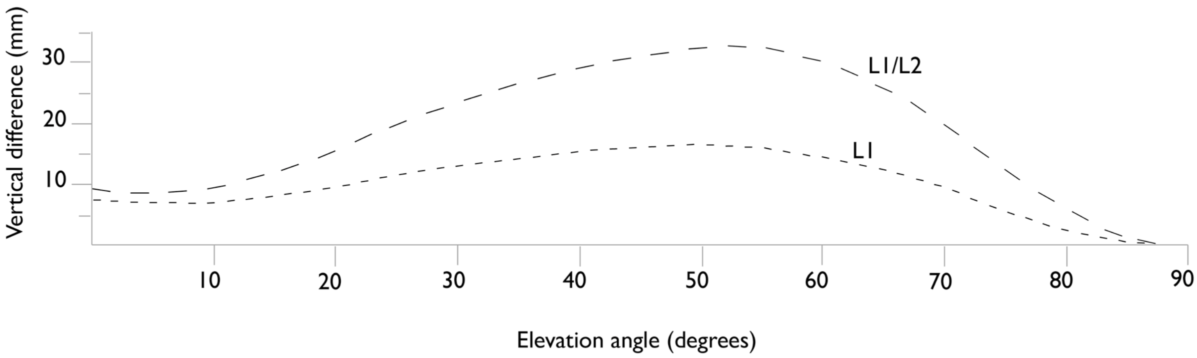
5.3.3 Antenna phase centre variations

Until the late 1990s, antenna phase centre variations were not modelled as part of the GNSS processing techniques. Such variations of the electrical phase centre of a GNSS antenna are a function of the elevation and azimuth angle between the receiver/antenna and a satellite. These variations are particularly evident in the vertical direction and differ in amplitude and phase for different types of GNSS antenna. If the same type of antenna is used on a relatively short baseline, the antennas' phase centre variations will be cancelled out because both antennas have practically the same elevation angle to a particular satellite. However, as baseline length increases, the elevation angles to a satellite from both ends of a baseline differ and the antenna phase centre variations become more significant. Furthermore, if different GNSS receiver/antenna types are being used, then the different antenna phase centre variations will certainly not be cancelled.

In studies, Schupler and Clark used laboratory (chamber) tests to determine the elevation and azimuth angle dependent antenna phase centre variations for a Trimble 4000 SST/SSE and a Rogue Dorne-Margolin antenna. They showed that the vertical differences between these two antenna types can reach 35mm at an elevation angle of approximately 55 degrees. Even more important, for high accuracy height determination, is the fact that this effect can be worsened through the use of tropospheric scale factors, without antenna phase centre modelling.

Figure 5.1 below shows the phase centre variations between the Trimble GNSS antenna and the Rogue GNSS antenna. These biases feed directly into the end co-ordinates and so are very important to quantify and correct for in high-accuracy surveying. The two curves show how the phase centres vary on both the L1 frequency and dual (L1/L2) frequencies, plotted against satellite elevation. It should be noted that this diagram is just one example of this particular operational difficulty, and antennas from other manufacturers will exhibit different behaviour when compared against each other. In some cases the differences may be negligible, whilst in others they may be more than those shown in the diagram.

Figure 5.1: Vertical differences in the phase centres of a Trimble 4000 SST/SSE Geodetic antenna and a Rogue Dorne-Margolin antenna



The phase centre variation is now modelled in one of two ways; either relative to a well-defined standard antenna, or absolutely through using either real or simulated signals. The ability of a software processing package to be able to include these antenna models may be of particular benefit to users. It allows the combination of the user's receiver data with data from existing networks of permanent GNSS receivers, which may be of many different types. It is recommended that the surveyor confirms that this facility is available within any software to be used for advanced processing of projects which include data from different receiver types. For RTK use, it is also important to understand which antenna is being used at the base – if this is different from the rover, then the antenna phase centre bias should be taken into account for the most demanding accuracies. (Surveyors should make themselves aware of the current (2009) advances within absolute phase centre research and its applications. More information can be found at www.research.cege.ucl.ac.uk/GNRG/index.html)

5.3.4 Use of GNSS under vegetation cover

GNSS has been proven to still work well under vegetation cover, such as a tree canopy. However, there may be a significant loss of signal and a corresponding increase in the signal/noise ratio (SNR). This is particularly dependent on the moisture content of the vegetation, and on the type of vegetation. The higher the water content, the greater the signal loss. At the limit this may result in complete signal loss, which will cause the loss of satellites from the position solution, particularly in dynamic surveys when the GNSS equipment is moving to capture the survey data.

In these cases it is far better to establish tertiary or secondary control using a medium precision survey method at the edges of the vegetation where there is a clear view of the sky. Further control can then be added under the vegetation canopy using a traditional traverse and spirit levelling method. Detail survey observations should also be carried out under the vegetation canopy using a traditional method, as RTK methods are not satisfactory in these marginal conditions.

6 Co-ordinate reference frames or systems?

As stated in Part 1, it is common to apply transformations to co-ordinates generated in the mathematical reference system of GNSS. This section introduces some of the important terms that should be considered in relation to co-ordinate systems and transformation process. Co-ordinate systems are discussed with an explanation of the guidelines as to why certain types should be selected over others for given projects and applications (Part 1, section 3.4). Finally, the process of co-ordinate transformation is discussed and some numerical formulae are given for the general cases.

6.1 Description of the earth

6.1.1 The geoid

The geoid is the equipotential surface (a surface where gravitational potential is constant) of the earth's gravity field which best fits global mean sea level. Heights referred to sea level are therefore related to the geoid and are termed orthometric heights. Sea level changes with time, and so most countries define the height of one point with respect to mean sea level over some time period and refer to this defined point as the levelling datum. Positions determined by geodetic astronomy are related to the geoid in as much as the axes of the instrument being used are aligned in the direction of, and at right angles to, the direction of gravity.

6.1.2 The ellipsoid

The mathematics of computing the geoid are complicated, and various approximations to its shape have been made. As a first attempt, a spherical earth introduces negligible error for some cartographic purposes; the attraction of this choice is that it is a surface with constant curvature. However, an ellipse of rotation, with semi-minor axis in the polar plane and semi-major axis in the equatorial plane, is a better match to the geoid. This shape (the ellipsoid) has been used for geodetic purposes for over two hundred years. A variety of 'best-fitting' ellipsoids (mainly national, regional or global), each with a different size and orientation to the earth's spin axis, have been used.

6.1.3 Datums and co-ordinate frames

Each GNSS system has its own datum: for example GPS uses WGS 84. A datum in this context is essentially a set of conventions, constraints and formulae which define it without recourse to a physical infrastructure. In order to use this datum practically it must be physically realised. This is achieved by means of a known network of points with defined co-ordinates, known as a terrestrial reference frame (TRF). Examples of such frames are:

- US Broadcast TRF (military tracking stations) – realises the WGS 84 datum and currently precise to about 5cm (see www.fig.net/pub/vietnam/ppt/ts06b/ts06b_higgins_ppt_3792.pdf; all stations are now updated to realise ITRF 20nn.05)
- IERS ITRF – realises, in name, the ITRS datum rather than WGS 84 although in practice the two are practically identical. The frame is associated with a point in time and thus has a stated epoch
- European TRF – geographically fixed realisation of the ITRS datum at a particular epoch in time. It is fixed to defined reference points and moves with the European tectonic plate. ETRS89 was coincident with ITRS at the start of 1989 (1989.0) and has since been diverging from the WGS 84 and ITRS datums.

It is possible to transform ITRF co-ordinates to ETRF co-ordinates by way of a six-parameter transformation (published by the IERS).

Epoch dates are stated as years and months, and written as YYYY.M (e.g. 1999.7). Users of precise ephemeris data will receive co-ordinates related to the current epoch, but if survey campaigns are to extend over long periods, the epoch date to be used should be stated.

The International Standardisation Organisation (ISO) produces numerous internationally recognised standards relating to geomatics and geodesy.

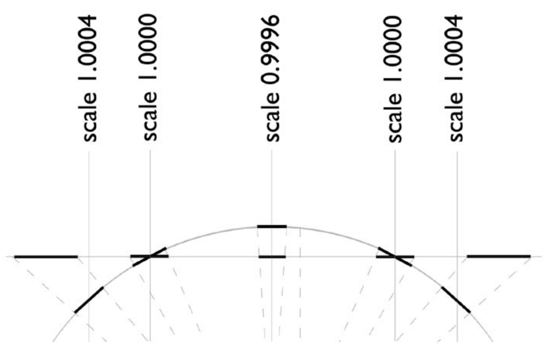
Members may find it useful to refer to the geodetic conventions contained within ISO 19111:2007: *Spatial referencing by coordinates*.

6.1.4 Projections

A projection is required to transfer measurements and positions from the ellipsoid onto a flat surface suitable for making into a map. For example, in Great Britain, the Ordnance Survey uses a modified version of the Transverse Mercator projection. In a simple Transverse Mercator projection the surface of the local ellipsoid chosen to represent the earth is represented on a cylinder which touches this ellipsoid along a chosen meridian and which is then unwrapped. The scale is therefore correct along this central meridian and increases on either side of it.

The modification often made to the projection is to reduce the scale on the central meridian by a factor of 0.9996. The projection then becomes correct in scale along two lines nearly parallel with and on either side of the central meridian about two-thirds of the way between it and the edges of the projection. On the edges, the projection scale will have increased to approximately 1.0004 of nominal figure. The advantage of this modification is that it extends greatly the area covered by the projection within an acceptable distortion of scale. This is shown in Figure 6.1.

Figure 6.1: Scale factor



The horizontal line represents the map surface lying at true scale line. The central area has a scale of less than one, the outer area scale is increasing up to maximum of 1.0004. The RICS Geomatics client guide, *Map projection scale factor*, available from www.rics.org/mappp, is an invaluable explanation and aide-memoire on this sometimes complex subject.

There are many other types of projection. They are of differing mathematical types and allow the various different shapes of countries to be represented on flat surfaces. In the above example, the Transverse Mercator projection is a cylinder, thus it is particularly suitable for north-south countries. In the case of countries that extend predominantly from east to west, a Lambert Conformal projection might be used; this is a cone which touches the ellipsoid along a chosen line of latitude. (Further information on the large range of different projections that exist for the many countries of the world can be obtained from *Map Projections – A Working Manual* (J.P. Snyder, USGS paper 1395).) In all cases, however, the projection is a set of numerical constants and mathematical formulae which are applied to ellipsoidal co-ordinates to obtain the familiar eastings and northings used in mapping.

6.2 Co-ordinate systems

Any point on the earth's surface can be referred to either the graticule of latitude and longitude (curvilinear co-ordinates) on the computation surface (the ellipsoid), or a three-dimensional cartesian system with an origin at the earth's centre of mass. Rectangular cartesian co-ordinates are easier to manipulate than ellipsoidal co-ordinates, but give no concept of height above sea level, or location on the surface. Either of these co-ordinate systems can be converted into easting and northing projection co-ordinates.

Each system has its particular advantages, but three principal reasons for using ellipsoidal co-ordinates are:

- they are commonly used and accepted in geometrical geodesy
- they make use of closed formulae, meaning that definition is exact
- an ellipsoid positioned close to mean sea level is the first approximation to the gravity potential.

6.2.1 Ellipsoidal co-ordinates

There are many standard ellipsoids on which curvilinear co-ordinates can be expressed. The positioning of the ellipsoid relative to the earth's surface is as arbitrary as the selection of the ellipsoid itself. The defining parameters of a particular country's geodetic reference system require both ellipsoid and datum to be given. These are:

- length of semi-major axis (a)
- flattening of spheroid (f)
- geodetic latitude and longitude of the origin (ϕ, λ)
- geoidal separation at the origin (N)
- two parameters which align the minor axis to the spin axis (CIO/BIH).

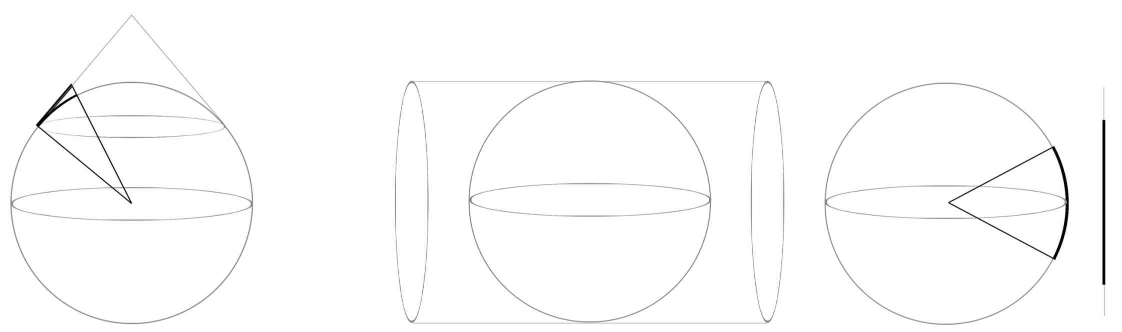
6.2.2 Cartesian co-ordinates

Cartesian systems are referred to an assumed earth centre. Although terrestrial ellipsoidal co-ordinates are implicitly referred to an inertial frame by the use of the CIO/BIH system, the definition of a geocentric datum is more explicit. The parameters defining a cartesian system might be:

- earth's gravitational constant (GM)
- earth's angular velocity (ω)
- speed of light (c)
- co-ordinate set of defined terrestrial points C{Px,Py,Pz}.

For the GNSS system, which involves satellites above the earth in addition to the receivers and GNSS infrastructure on the earth, the cartesian co-ordinate system is the most useful.

Figure 6.2: Conic and cylindrical projections



6.2.3 Projection co-ordinates

For most general survey and mapping projects these are the most useful co-ordinates. The surface of the earth is represented by a grid of eastings and northings and mapped features, structures or other items all have specific grid co-ordinates. Simple numerical grid computations can be made between any of the mapped items such as distances, areas or volumes, hence these are used in almost all engineering and mapping applications.

It is therefore clear that since cartesian co-ordinates are most suitable for the GNSS system and projection grid co-ordinates are most suitable for surveying and engineering, transformations must be made between the two systems. In most cases these transformations are applied by the manufacturer within the GNSS receiver systems and processing software. Since transformations are a set of mathematical formulae and numerical constants, some small differences may be found between different manufacturers' methods of transforming to the same co-ordinate system.

6.3 Co-ordinate transformations

The next section provides the relevant formulae for transformations between various co-ordinate systems, together with a brief explanation, when necessary. No attempt is made to explain the detailed derivation of the formulae. Such information can be found in various textbooks (e.g. Bomford, 1980) listed in Appendix C.

6.3.1 Ellipsoidal to cartesian transformations and reverse

The following formulae are suitable for conversion of ellipsoidal co-ordinates (ϕ and λ) to cartesian co-ordinates (*x*, *y* and *z*). In these formulae, the x-axis is defined as being parallel to the conventional zero meridian of Greenwich, the z-axis parallel to the CIO and the y-axis at right angles to these two (eastwards). The cartesian system may be geocentric or referred to the vertical at some specified point.

$$x = (v + N + h)\cos\phi\cos\lambda \tag{6.1}$$

$$y = (v + N + h)\cos\phi\sin\lambda \tag{6.2}$$

$$z = ((1 - e^2)v + N + h)\sin\phi \tag{6.3}$$

Notice that the height of the point is (N+h) above the ellipsoid. Thus, equations 6.1, 6.2 and 6.3 presuppose knowledge of the geoid/ellipsoid separation (N).

The reverse transformation, from cartesian to ellipsoidal co-ordinates, does not produce such closed formulae. The formulae for this reverse transformation are:

$$\tan\lambda = \frac{y}{x} \tag{6.4}$$

$$\tan\phi = \frac{z + e^2 v\sin\phi}{\sqrt{(x^2 + y^2)}} \tag{6.5}$$

Approximate values of ϕ and λ are used and iteration gives rapid convergence.

Another alternative is the closed formula due to Bowring:

$$\tan\phi = \frac{z + (e')^2 b\sin^3\theta}{p - e^2 a\cos^3\theta} \tag{6.6}$$

where: $(e')^2$ the second eccentricity^2 $$= \frac{e^2}{(1 - e^2)} \tag{6.6a}$$

$$p = \sqrt{(x^2 + y^2)} \tag{6.6b}$$

$$\tan\theta = \frac{za}{pb} \tag{6.6c}$$

$$H = (N + h) = \frac{p}{\cos\phi} - v \tag{6.7}$$

Or $$(N + h) = \sqrt{(x^2 + y^2)}\sec\phi - v \tag{6.7a}$$

(using Bomford's notation)

It is important to note that again *N* needs to be known (see paragraph 6.3.4), and that (*N*+*h*) is determined when using equation 6.7. (*N*+*h*) is the ellipsoidal height and is not a height obtained by spirit levelling.

In summary, to convert from:

- **ellipsoidal to cartesian**: use equations 6.1, 6.2 and 6.3
- **cartesian to ellipsoidal**: use equations 6.4, 6.5 and 6.7.

Evidently, different mathematical models can exist for the transformations, hence the small differences that may occur when using different manufacturers' methods of transformation. These differences will manifest as small systematic offsets between two groups of local co-ordinates when transformed by two different methods. The most important issue when working on high-accuracy projects is to be consistent and use the same method of transformation and software. Thus any small differences in co-ordinates will not be propagated into a project and distort the geometry of a survey undertaken using GNSS.

6.3.2 Transformations from ITRS89 ellipsoid to local ellipsoid

This is the transformation most commonly known as a 'datum transformation'. The local ellipsoid can be defined as the ellipsoid used for the co-ordinate system in a particular country. As a historical example, in France the Clark 1880 ellipsoid is used for the national co-ordinate system. The modern French national geodetic co-ordinate reference framework is RGF93 which is based on a GRS80 ellipsoid realised through WGS84. Over the course of history, as different countries produced their own co-ordinate systems, many different local ellipsoids were used. This was due to one particular ellipsoid representing that country better than another. In addition, they also were assigned different origin points and directions of the fundamental axes. Therefore, to relate all of the world's different ellipsoidal systems to the single reference system of GNSS, 'datum transformations' are required. These can be split into the following types: Molodensky, Helmert and multiple regression equation (MRE).

- **Molodensky formulae**: computation of $\Delta\phi$, $\Delta\lambda$ and Δh between the frames
- **Helmert transformation**: computation of ΔX, ΔY, ΔZ, (three translations), θx, θy, θz (three rotations about the axes) and k (scale factor) between the frames
- **multiple regression formulae**: computation of $\Delta\phi$, $\Delta\lambda$ and Δh between the frames, but allowing for local datum distortions using a polynomial expression.

In fact, the Molodensky formulae are related to the Helmert transformation; it is the same process, but in the curvilinear (geodetic co-ordinate) sense, rather than the rectangular co-ordinates of the Helmert transformation. In many surveys, the transformation most commonly used has been that of the 'seven-parameter transformation', or the Helmert transformation. As they were the simplest to implement in the software, this was done and many older projects were transformed in this way. National mapping agencies have, in some cases, produced their own refinements to these original transformations. It is recommended that the current datum transformation published by those agencies is followed as best practice.

6.3.3 Transformation to projection co-ordinates

Once a 'datum transformation' has been carried out the map projection formulae and numerical constants are applied to the ellipsoidal co-ordinates to obtain projection grid co-ordinates. Due to the large number of different map projections that exist, it is not practical to detail them all here.

In some countries, other methods of obtaining projection co-ordinates may exist. For example, in Great Britain the Ordnance Survey has produced a grid look-up table to convert from ETRS89 to the national grid. This was necessary to cater for the large distortions in the way the national grid was historically realised on the ground. None of the rigorous mathematical methods, as outlined in section 6.3.2, was sufficiently accurate for the whole country, and therefore a look-up table was the most suitable method for transformation.

Projection co-ordinates are usually subject to a final transformation into a local grid. For small and medium-sized land surveys this is the final, true scale, flat earth co-ordinate system often specified by the client. This transformation has a local grid origin and no scale factor, to ensure measurements on a final survey drawing or in a digital model relate exactly to those found on the ground.

For large projects, the area of survey may not be compatible with the country's map projection. For example, one end of a large east-west project in Great Britain would have a very different projection scale factor to the other end. The adoption of a central value may introduce unacceptable distortions at each end of the survey. In general, for such projects it is best to carry out the whole of the survey in ITRS89. A custom projection for the project may then be chosen, based on the criteria in section 6.1.5.

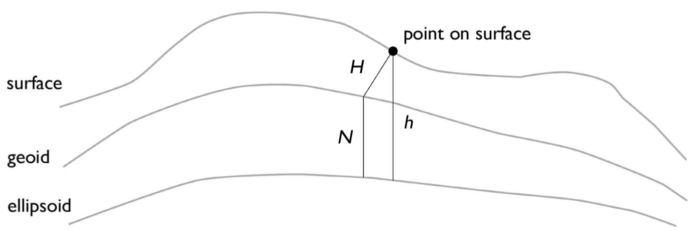
Due to the many complex factors that exist in co-ordinate systems and the transformations between them, it is critical in any GNSS survey project to clearly describe which transformations have been used. Use of the EPSG Geodetic Parameter Dataset (see www.epsg.org/geodetic.html) is recommended to reference any parameters adopted, and the manufacturer's software type and version should be quoted in addition to all the steps used in generating the local grid co-ordinates. This will ensure that any future survey work is totally compatible with that previously carried out.

6.3.4 Height transformations

There is a special treatment required to calculate the heights of points observed by GNSS. It is simpler to envisage the reverse transformation from levelled orthometric heights, to those observed by GNSS. Before any co-ordinate transformations take place, the elevation height of the control point in the national datum (e.g. to mean sea level (MSL)) must first be converted from an orthometric height to an ellipsoidal height. Before any datum transformation, this orthometric height is the height of the control point above the geoid in that area, usually given the symbol *H.*

However, what is required is the ellipsoidal height relative to that ellipsoid used in the national datum. For example, in Great Britain Ordnance Datum, Newlyn height (*H*) must be converted into the Airy ellipsoidal height (*h*). The difference between the two heights is the height of the geoid above the ellipsoid, or geoid-local ellipsoid separation, *N*. This is shown in Figure 6.3 with an exaggerated separation for clarity.

Figure 6.3: Height relationships



Thus the general equation to relate heights can be written as: $h = H+N$

Where:

- h is the ellipsoidal height
- H is the orthometric height
- N is the geoid-ellipsoid separation (undulation or geoidal height).

The ellipsoid used for a local datum was selected when the datum was defined, and is usually the best-fitting ellipsoid to the geoid in that part of the globe. In the local datum the value for *N* is therefore typically small; in Great Britain for example the maximum separation between the Airy ellipsoid and the geoid (MSL Newlyn) is only 2.5m over the whole of the country.

However, with a global geocentric ellipsoid such as ITRS89, the separation can vary dramatically. In Great Britain the geoidal height is approximately 50m, whilst in areas of the Middle East it is -10m; i.e. the ellipsoid is 10m above the geoid. Thus, height corrections for the geoid/ellipsoid separation are extremely important when transforming ITRS89 geodetic latitude, longitude and ellipsoidal heights to co-ordinates with a local orthometric height.

There are many different geoid models published and these provide the basic look-up table for orthometric /ellipsoid separation values over a given area. Both global and country models exist, and most give the values between the global or local geoid and the ITRS89 ellipsoid. The models are incorporated differently into GNSS manufacturers' software and it is good practice to check which model, and associated accuracy, is being used.

In practice, the reverse of the procedure is carried out. GNSS observed heights are transformed from cartesian to ellipsoidal co-ordinates, then by an application of the orthometric/ellipsoid separation model, the resultant ortho heights are produced.

Depending on the local situation, best practice differs:

- use GNSS plus the orthometric/ellipsoid separation model to bring orthometric height onto a site. Traditional spirit levelling should then be used to promulgate the orthometric height around the site
- include at least three or four height control points in a survey network which have reliable orthometric heights. These orthometric heights can then be compared with the computed values from the national control and the application of the geoid model. The figures may show up a bias in the model, especially if it is to a large grid global geoid model. They can be held fixed in any final adjustment if required.

6.3.5 Co-ordinate transformation issues in GNSS

In GNSS land surveys, there are several key co-ordinate system and transformation issues that should be considered.

First, there is the use of national control points. For any project a minimum of three but preferably four points should be obtained to control the survey network. An indication of the actual accuracy of these points should also be obtained from the national mapping agency. This needs to be considered, as older control values from triangulation surveys will not be as accurate as GNSS values. If these older 'fundamental co-ordinates' are held fixed in any network adjustment, the GNSS survey geometry will be distorted and errors will result in the survey. Therefore, good quality, recently surveyed national control points should be obtained for any survey which requires a tie to a national grid.

Secondly, if no national grid co-ordinates are required and no national control is used for a survey, it is important to use an accurate position in ITRS89 as the basis for the survey. If this is not done, scale errors will result in the baselines observed from this base point. The approximate magnitudes are shown below in **Table M**.

Thus, it is important to take a single point position (SPP) using at least a low-precision static method, preferably using dual-frequency data (see section 5.1). The results of this SPP should also be quoted in any survey reporting, together with an estimate of the accuracy of the final ITRS89 position. If the survey is required to be later placed on the national grid, errors will also result as the SPP ITRS89 point used for the survey will only be accurate to a few metres. It will also be difficult to ensure correct transformations between co-ordinate systems if future work is to be carried out.

Third is the use of manufacturers' own single-step transformations. These are often offered by GNSS equipment manufacturers as a simple method of obtaining true scale (flat earth) local grid co-ordinates from ITRS89. In the worst case, an arbitrary ITRS89 point is used with the manufacturer's own single-step transformation for the whole survey. If future work is to be carried out using another manufacturer's equipment, many potential problems could arise. It is far better to conduct the control element of the survey separately, based on precise ITRS89 points and using rigorous transformations from ITRS89 to the final local grid. It is best practice to use single-step transformations generated from a set of four or more points that have accurately surveyed co-ordinates in ITRS89 and in the local grid. It is critical that detail observations are completely within the control framework when using single-step transformations.

If a manufacturer's single-step or similar transformation is used, all parameters and transformation types should be quoted in any co-ordinate listing or in the survey report with equipment and software versions. A back-up copy of the survey should also be kept in ITRS89 for any other later transformations as required.

Table M: Scale error magnitudes

Error in true ITRS89 position (m)	Baseline scale error (ppm)	Approx. error at 5km
2m	0.3	2mm
10m	2.6	13mm
100m	25.5	130mm

7 Quality issues

Previous sections have described the various methods and techniques used to collect and process data to determine position. Mention has been made of various factors which can degrade results. This section specifically addresses quality issues in GNSS surveying.

In GNSS surveying the instruments and software are often a totally enclosed system and the co-ordinates which appear on a screen often appear with little evidence to indicate that they are indeed the correct values. Two distinct types of quality measures should be considered: those related to operational processes and those related to the acquired data. As in all surveying activities, a set of specific quality control procedures are required that can be undertaken during the survey to ensure that it is executed in the most effective way, with the minimum opportunity for errors to occur.

7.1 Survey planning

Generally, any form of surveying activity should be performed by following procedures, creating a process stream which leads to fulfilment of the original specification or scope of work. The appendices to this guidance note contain details of typical procedures and specifications. Within a procedure or specification, aspects of quality control should be considered, i.e. ways of ensuring that the best possible care is taken during a survey to achieve the best possible result.

To achieve this in practice, it is recommended that the planning process should include a simple, straightforward quality plan, which will reference the necessary practical procedures. This will explain what will be done during the execution of the survey to assure both the client and surveyor of the controls being exercised over quality.

No generic plan can be written to cover all GNSS surveys, due to the diversity of the tasks, methods and personnel who perform the works. The quality plan could be as simple as a single page of basic quality control procedures, or a complete manual for a large project. It should cover:

- how quality control of the field work and field data will be achieved
- how quality control of the office procedures will be achieved
- any QA management systems and procedures of the survey company
- any work instructions of the company (including health and safety procedures).

Field work aspects should include items relating to data download and back-up from receivers, staffing and logistic requirements, storage of data, pre-processing of data, storage of equipment (overnight) and supply of back-up equipment. Office procedures would include some of these and other relevant aspects, such as data back-up and archive.

It is essential that all aspects of the survey and data handling process are considered at the stage of producing the quality plan, since it will not always be immediately apparent in the subsequent fieldwork that inadequate observations have been obtained. A considered redundancy of data is always preferable to a shortfall which requires re-observation to obtain a solution to the required quality.

7.2 Survey design

While following procedures in a quality plan is important for the performance of the survey and will help to avoid procedural mistakes and accidents, the actual quality of the data and GNSS results is the most important aspect of quality control. The following sections detail the best ways to provide quality control to GNSS survey data, ensuring the best solutions are obtained from the raw observations, and that the derived co-ordinates have the best possible values.

7.2.1 Network design

Despite the perception that GNSS is a high-tech activity, the basic rules of surveying still apply to GNSS networks. The principles of robustness, overall cover and repeatability apply. The latter aspect is often overlooked.

In a GNSS survey, trivial baselines exist within an observing session. For example, if three GNSS receivers are observing at the same time in a static control survey, there are three GNSS baselines that can be processed. Two of these are independent: however the third, computed from the same observations, is just the vector difference of the other two. This is known as a trivial baseline, and it is best practice not to compute this baseline. The processing and inclusion of trivial baselines will give highly correlated measurements in the network adjustment. This will cause errors in the stochastic modelling, and incorrect results in the adjustment. For trivial vectors it is better to have a second set-up, during another session and perhaps on a different day, or to use a different time interval of the same session.

It should rarely be assumed that a survey is to be a once-only, stand-alone activity, unless the specification makes this quite clear. The normal assumption should be that further observations and activities, not always undertaken by GNSS methods, will take place over an extended period of time. Adequate permanent reference points should be located, with due consideration to any future construction works, so as to facilitate direct linkage with later surveys. In particular, the situation may arise where there is some variation between two networks that are unconnected but adjacent. This could be due to different fundamental control being used for each. When designing a new survey, it is good practice to ensure that some common network points exist within the two adjacent survey areas, to enable correlation and computation of co-ordinate differences.

7.2.2 Network shape

Networks should be designed to completely encompass the area of the survey detail, whenever access permits. Within the network areas an individual point will be constrained by the residuals of the network stations, but observations outside the enclosed figure will have little constraint and a rapid increase in error can occur, even over short distances.

Closed loops provide the best geometrical figures, more sessions observed for each baseline, generally leading to better results. For highest accuracy networks, the repeating of one or more previous baseline sessions in the next group to be observed provides additional robustness. Radial baselines in a network should be avoided for main figures, as these do not provide independent checks between the outer points. Although multiple radial set-ups would provide such checks, better geometry, statistical certainty and economy of operation will be achieved by use of traditional closed loops or figures similar to older triangulation chains.

7.2.3 Linkage to national control

When connecting survey areas to national control, it is better to design this part of the network separately where appropriate. In some cases, long lines may be needed to connect and tie into national control, especially if the data is from an active system where the three nearest control stations could be up to 100km distant. In these cases it is far better to have a 'zero order' network to connect three or four of the primary control points to the national control. This will ensure the baselines in the network are of a similar type and will improve the stochastic modelling in a network adjustment. These primary points can then be fixed in this way with their associated precision values, and used for the 'primary survey'. This is particularly important when combining short baselines of 1 to 3km length, with baselines that connect to national control of between 50 and 100km. It is not good practice to observe as many points as possible, put all the data into the processing software and use it as an automatic machine, hoping for the best. Far better is a rigorous step-by-step approach of loading vectors and processing from the whole to the part, just as in traditional surveys.

7.3 Field procedures

Field procedures adopted will depend upon the size and rigour of the survey being undertaken, as well as the co-ordinate system specified. For small control or detail surveys on an arbitrary local grid, the ITRS89 co-ordinate for the reference station should be accurate to about 10m. This will limit scale errors. (See **Table M**, p. 48.)

7.3.1 Control surveys – high-order

For surveys requiring the highest precision (sub-centimetre), each survey will require a geometrically well-balanced design scheme, which should include several redundant observations and will always be observed using static survey techniques.

The requirements to achieve the highest quality could include the following:

- two independent sessions, being observed over each baseline at different times to different satellite constellations
- three or more existing (ITRS89) control points included in any scheme
- antennas oriented to true north at all stations
- where possible, sessions planned to enable a minimum of five satellites to be observed, avoiding high peaks in PDOP
- log all receiver and antenna types used in the scheme, to allow for antenna phase centre variation calculations to be made
- session duration and epoch separation as provided in **Table D3** (p. 14).

Independent sessions, with a significant time interval between them, reduce the likelihood of external influences creating systematic errors. The changes in satellite geometry provide a second set of calculations, which should identify any weakness in the derived solution. For precise control, the orientation of all antennas to north eliminates eccentricity effects. Five satellites are normally considered to be the minimum to provide adequate statistical redundancy to the observations. It needs to be noted that they should be well distributed across the open view of the sky and at reasonable elevations.

7.3.2 Control surveys – low-order

The requirements for lower-order control surveys could be:

- dual-frequency receivers with the ability to measure carrier phase on L1 and L2 signals must be used to enable the rapid static technique. It is also recommended that the GNSS receivers to be used should have the manufacturer's rapid-static firmware loaded
- two or more existing (ITRS89) control points should be included in any scheme
- careful planning for short observation times with radio/cellular telephone contact between operators. Note that cycle slips can be caused by some radio communication frequencies, particularly on the weaker L2 signal (see section 5)
- session duration and epoch separation as provided in **Table D3**
- post-processing software should have the required modules to cater for fast static data.

It is important to be aware that when rapid static data is observed, multiple occupations may be contained within a single data file.

7.3.3 Recording of field notes

Booking sheets are vital to ensure the correct recording of antenna height, point name and data file name for the occupation. These are the most important factors to record in any GNSS survey. In addition, it is good practice to record the following additional items to assist in the data processing stage of the survey: date, time of occupation, epoch setting, elevation mask, equipment serial numbers (for fault tracing), weather observations, obstructions to the view of the sky, and any other relevant observations. The sheet can also be used to record times when cycle slips are observed to occur and when loss of lock or a new initialisation occurs in real-time surveys.

A recent almanac should be used with appropriate planning software to generate a sky plot of satellite coverage during the survey. This will clearly show the times during the day when satellite coverage is better than at others. It can also be used to plan the occupations for the day, or to plan a break in the survey when satellite coverage is poor. It is best practice for the surveyor to take a plot on site, showing the predicted number of satellites and expected PDOP or GDOP values.

7.3.4 Detail surveys

Dynamic methods are most appropriate to detail surveying. The basic method is to keep one receiver fixed at a known control station (base), whilst one or more other receiver(s) (rover) move around the site, as outlined in sections 4.3 and 4.4.

For surveys requiring detail or co-ordinates to be captured at accuracies better than 100mm, high precision dynamic techniques can be used, either in real time or post-processed. It is best practice to use a real-time system such as RTK for these surveys. **Tables D1 to D3** can be used to select an appropriate survey method, given a particular accuracy specification.

The field procedures adopted should incorporate the following best practice guidelines:

- the base stations should be part of an existing or previously surveyed network, with accurate co-ordinates to better than ± 5m in ITRS89
- the technique should be limited to 10–15km baselines
- if further base station set-ups are used (for example in a long linear survey), these should be tied as part of a main network to other base stations used. The survey should also include common points, observed from each adjacent base
- take antenna phase centre variations into account if different types of antenna are used
- if any new tertiary level control is observed, each new station should be co-ordinated twice, once from each of two base control stations to ensure an independent check
- both receivers must maintain lock on at least four satellites throughout the session, hence this technique should only be used in areas where loss of lock is likely to be minimal, e.g. open spaces, clear of vegetation and structures
- on starting survey for the day, once the receiver has completed initialisation it is good practice to make a separate check on a known station, to ensure the receiver has the correct integer solution and the base has the correct co-ordinates
- when a loss of lock occurs during the survey, a previously co-ordinated point should be revisited in order to check the re-initialisation of the receiver.

There are also more specific issues that relate to quality control of real-time systems; these are covered in detail in section 7.4.

7.3.5 Medium and low-order detail surveys

For detail surveys, or positioning that requires a precision at the 100mm to 1m level, differential GNSS techniques can be used. These can be real-time or post-processed, and in all cases the surveys are not subject to the same loss of lock criteria as higher-order surveys. The guidelines below could be followed for fieldwork:

- occupy known points during the survey – these could be either national control points, or other control points in the survey area measured using a higher-precision method
- observe map check points if data is to be fitted to a background map. This will ensure the data is consistent with a map background and will allow the accuracy of the background map to be assessed;
- ensure the positional data logged includes the number of satellites, DOP values, estimated precision and the standard deviation of any multiple DGNSS positions logged for a point
- try to use the equipment where clear sky views are available. Despite manufacturers' claims that DGNSS equipment will work in wooded and other enclosed areas, it is best practice to use another survey method in such areas, for example a laser distance/compass system to provide offset points in low-precision applications.

7.3.6 Static positioning

Due to lower accuracy requirements, the quality control of the field procedures for positioning tasks is far less rigorous than for static or dynamic surveys. The main quality issue is to ensure the file name for any logged data is noted and booked in the field, with the point names. The manufacturers of GNSS instruments provide waypoint storage for points, and these should be used to log general points in the field. It is also best practice to keep a copy of all co-ordinate data in ITRS89 for later transformation if required. This will ensure the desired co-ordinate transformation is used, which may not be the one supplied by the manufacturer in the GNSS receiver.

7.4 Quality control of real-time systems

Real-time systems are a highly productive GNSS technique, in that the surveyor knows the system has worked and that sufficient data has been logged before vacating the site. The surveyor knows immediately that the data has been successfully captured at a suitable level of precision, although the absolute accuracy is unknown.

As no post-processing and adjustment is available to provide statistical analysis, the quality control parameters for these surveys must be available in real time to the surveyor.

The surveyor should view, in real time, precision figures determining solution quality to check the impact of any multipath problems or accuracy degradation at a point and should set tolerance values into the datalogger making it impossible to record sub-standard data. In post-processing, multipath would only be detected by a point failure or inability to initialise. Longer-range, high-accuracy, real-time systems are also offered by some manufacturers. These introduce further issues with respect to co-ordinate control, as well as initialisation strategy and reliability.

In all cases when using network RTK the *Best Practice Guidance Notes for Network RTK Surveying in Great Britain* (see www.tsa-uk.org.uk) and the manufacturer's guidelines should be followed. In particular it is good practice to initialise the survey twice when using either real time or post-processed network RTK. For example, an on-the-fly initialisation could be made first, followed by a second initialisation on a known point. This ensures a check on the initialisation is made at the start of the survey. In addition, further check measurements should be made to previously surveyed points which are part of a larger primary control network, and these check measurements can be used to assess the absolute survey accuracy.

Real-time dynamic systems produced by manufacturers may well offer ad-hoc indicators of quality and reliability. In the paragraphs which follow, definitive, best practice, real-time dynamic quality control parameters are outlined.

7.4.1 Real-time dynamic systems quality control

In the high-precision real-time dynamic (RTK) case, quality control can be split into two distinct operations:

- quality control of the system initialisation, and subsequent initialisations after a loss of lock
- quality control of the co-ordinates produced in real time.

System initialisation issues are covered in sections 7.4.4 to 7.4.6. For quality control of the co-ordinates produced in real time, the testing of integer solution sets within the manufacturer's software should follow a similar line to that used in the post-processing systems. Outlier detection should still be implicit, based on testing individual double difference phase residuals against a scaled RMS of all residuals. Variance ratio testing should be carried out by computing the ratio of the next best to the best solution variance and comparing it against a value computed using the Fisher distribution at the 95% value. More conservative ratio test values of 5.0 or above are usually used for real-time RTK systems.

7.4.2 Reporting of quality control

Much of this quality control will take place in the manufacturer's software and will not be visible to the surveyor. It is recommended that the following quality control parameters are produced for all detail points to give an indication of co-ordinate precision to the surveyor:

- the number of satellites being observed
- the *a posteriori* standard errors of the baseline solution (dx, dy, dz)
- 95 per cent confidence level error ellipse, as horizontal and vertical precision figures.

The final data output should present these with the co-ordinates of each point. Similar information should also be displayed on screen to the operator for every point observed and any points which fail should not be logged. This implies that the operator checks the screen for every point recorded during the survey; a more realistic option is to set up an acceptance value in the logger software.

7.4.3 Control point inclusion

In all real-time kinematic surveys it is vital that the site includes at least one high precision control point previously established using a static GNSS, or other technique. This allows real-time co-ordinates to be checked against a known reference. It also provides a convenient re-initialisation point within the site area. If the real-time solutions are to be later included to strengthen a network adjustment, or as tertiary control points, they should also include as a minimum the upper triangular elements of the a posteriori covariance matrix. The control points should also have a longer occupation period than the detail points, perhaps two or three minutes per point.

7.4.4 System initialisation

Operational procedures are generally simple; with a dual-frequency receiver, initialisation is fully automatic and can be realised while static or while moving (on-the-fly). Fully automatic initialisation, under normal conditions, is usually achieved reliably within a minute or so. To achieve centimetre accuracies, the rover tracks carrier phase and code phase (pseudorange) data and must initialise itself with respect to the base station. Initialisation is the term used to define the process of determining the carrier phase integer ambiguities; at least five common satellites must be tracked between the base station and rover with a PDOP of better than five. Before initialisation, the receiver may produce a coarser solution, within about a metre, but can converge within a minute or so to a few centimetres. Once initialised, the system switches to a fixed solution (ambiguities resolved) and precision improves to about a centimetre.

7.4.5 Incorrect initialisations

The initialisation process is very reliable, but incorrect initialisations can occur. Formal testing by a manufacturer should indicate initialisation reliability figures of at least 99.75 per cent. The level of reliability may also be a function of time, with less reliable initialisation figures being specified for shorter initialisation periods. Different systems respond in various ways, and this should be taken into consideration when preparing quality procedures. In all cases, best practice is to initialise in completely open areas with no possibility of multipath or other interference to satellite tracking.

For RTK initialisations, the production of three distinct quality control parameters is recommended:

- the ITRS89 co-ordinates of each initialisation point, their accuracy at the 95 per cent confidence level and the type of initialisation (i.e. known point, on-the-fly, etc.)
- integer bias values of the initialisation baseline solution
- ratio, variance, RMS of the initialisation baseline.

These latter two items should be provided by the software to give the surveyor an indication of the reliability of each initialisation, and should be checked after each re-initialisation with a duplicate field point taken to provide a physical check. All three should be logged as explicit quality control parameters in the survey archive for each initialisation and given in the final report if required.

7.4.6 Initialisation checks

A bad initialisation may result in position errors of at least 20 centimetres. The receiver may automatically detect and correct these events, given suitable satellite availability and geometry. This would normally take a few minutes, and this time could be considered as an initialisation or self-checking window. The rare occurrences of bad initialisations tend to be focused around lack of redundant satellite coverage or poor PDOP (e.g. five satellites only with a marginal PDOP), or at heavily multipathed locations. Operational procedures, such as satellite coverage planning or checking against known points, are best practice in these cases.

Similarly, observation periods where an initialisation has been followed quickly by a loss of lock and re-initialisation (i.e. within the time of a self-checking window) should be treated as suspect, and two checks should be done at known points in this segment.

A fixed solution, whilst requiring five satellites to initialise, can be maintained through periods when only tracking four satellites. In addition the fixed solution can be maintained through periods when the communications link is lost. The communications link provides satellite observations from the base station at the rover, in order that the firmware can compute the initialisation baseline solution. It is best practice to note when the communications link is lost, and to re-process any points captured, using post-processing software. In most cases the RTK equipment will flag the observations, but it is good practice to log these points on a suitable booking sheet in the field. If satellite lock is also lost when the communications link is down, it is good practice to complete a period of static initialisation according to the medium-precision static criteria given in section 1.3.

It is best practice, however, to ensure that the communications link is maintained for initialisations and survey points.

This can be done by planning the survey to ensure RTK baselines are kept short and the survey takes place in a location with a minimum of interference. A radio frequency scanner can be taken to marginal or unknown sites. This will aid selection of an optimum communications frequency. A repeater radio station could also be strategically located to ensure communication links are maintained.

7.4.7 L1-only receivers

Real-time Kinematic is also possible using appropriate L1-only receivers. This generally requires initialisation on a point where the co-ordinates have been previously surveyed. Some systems are available which offer automatic initialisation on L1 alone, but these tend to require longer initialisation times, often allied with a requirement to remain static during the process or to observe up to seven satellites if initialisation is to be realised. Real-time Kinematic on L1 only is also practically restricted to shorter ranges than L1/L2 solutions, and will suffer incrementally with increase in ionospheric activity. This technique is not recommended except at sites where the sky is totally open and there is no danger of losing lock.

7.4.8 Real-time DGNSS quality control

When using these systems for land surveys, it is good practice to ensure that more than one epoch of data is used at a point. Epoch settings of typically one second should be used, with five to ten readings taken per point, according to the requirements of the specification. This will allow the computation of the following statistical quality control measures for each point:

- number of satellites
- PDOP
- standard deviation of positions logged
- overall software estimated horizontal and vertical precision.

Other aspects of quality control, the derivation of specific quality control parameters and statistical tests for models used in DGNSS systems are well covered in the text, *Guidelines for the use of differential GNSS in offshore surveying* (these guidelines are under review and will be superceded in 2010 by *Guidelines for the use of satellite positioning*), published by IMCA (www.imca-int.com/divisions/marine/publications/199.html).

7.5 Office procedures

As part of the overall quality system, the processes involved in converting raw field data to useable co-ordinate information will now be considered. These include downloading and preliminary processing, full processing and key checks, adjustments and transformation to the final co-ordinate system.

7.5.1 Data handling and control

Downloaded raw data should always be fully backed up as an archive before any manipulation commences. Whenever possible, a preliminary batch process of data should be carried out immediately after completion of observations on site. This provides warning of possible processing problems while there is still an opportunity to carry out immediate re-observation of doubtful points. All such processing should be deleted after the data is confirmed to be adequate, to avoid it being treated as the final product. Full reprocessing with all controls applied can then take place and be used to supply the final data, as described below.

As part of the backing-up of information, consideration should be given to providing a RINEX format copy, since this is software independent and recoverable at any future date.

7.5.2 Data processing software

For the raw data observed in static surveys and dynamic (non-real-time) surveys, described in section 4, post-processing is required to obtain final co-ordinates. It is recommended that wherever possible, the software used is the current version offered by the GNSS hardware manufacturer whose equipment is used for the survey.

This will solve numerous incompatibility problems and also provide higher-precision results, since a manufacturer often has specific codes stamped on the binary data to aid the post-processing. If this is not possible, then it is recommended that data in RINEX format is used with the proposed software.

Most of the software used for baseline processing, loop closures, network adjustment and co-ordinate transformations has become increasingly automated. The result is that although more people can now successfully process GNSS data and use it practically for surveying tasks, fewer understand the processes which have to be applied to GNSS raw data. Advanced processing strategies are available within some packages, but these should only be used by experienced personnel with substantial expertise, since incorrect application of such techniques can introduce significant errors which are difficult to detect.

7.5.3 Quality of data

The important general elements of controlling the quality of data in post-processing are:

- ensuring the correct baseline solutions are processed and selected
- baseline observations outside the required precision are deleted or re-observed
- network adjustment is computed with a correct weighting strategy (stochastic model)
- co-ordinate transformations and projections are computed correctly.

Each of these important aspects is covered separately in the following paragraphs.

When attempting to obtain the best baseline solution from a set of possible options, the process of statistical testing is used in the manufacturer's software. Such testing falls into two distinct categories:

- measurement quality estimation during GNSS processing (RMS and standard deviation)
- the testing of integer solution sets (ratio).

7.5.4 Mathematics of processing

The fundamental measurement used by static and dynamic GNSS surveying systems for baseline estimation is the double difference phase observable during the final pass of processing. The fundamental observables for the final pass are usually one of the following:

- L1 fixed double difference
- L2 fixed double difference
- iono free double difference
- narrow lane double difference
- wide lane double difference.

GNSS processing software generally computes a root mean square (RMS) of the residuals for the chosen final pass double difference phase observable. This is then often scaled by a default factor (for example, 3), which corresponds to a number of standard deviations. Residuals computed from a least squares estimation are then compared with their scaled RMS values and, if they exceed it, are removed from any further estimation process. The alternative to specifying a fixed scaling factor is to compute a value based on the student's t-distribution at a specified confidence level (e.g. 95 per cent). This value is based on the degrees of freedom in the measurement process and the specified confidence level.

This then provides the following as an estimation of the measurement quality: RMS, in cycles or metres, and the standard deviation of the baseline components dx, dy and dz at the 95 per cent level. Error ellipses may also be computed with respect to the estimated co-ordinate solution.

Baseline differences between iterative solution types for the same baseline, such as wide lane and narrow lane combination and L1 fixed integer or iono-free fixed integer should also be inspected for variations larger than the expected measurement precision. This is a key check and is essential for all surveys.

For fixed integer solutions the testing of the different possible integer solutions is carried out. This is done by computing the ratio of the next smallest solution, to the smallest variance from the two integer solutions. There is usually a cut-off value, normally set at 1.5 for static baselines and 3.0 for post-processed kinematic baselines. The alternative to specifying a ratio cut-off value is to compute a value based on the Fisher distribution at a specified confidence level (e.g. 95 per cent). The 1.5 value corresponds to the 95 per cent confidence level. Thus, a ratio is also usually given for each fixed integer baseline.

7.5.5 Key parameters and checks

Many manufacturers have their own method of selecting the best baseline solutions from a set of available solutions. In addition it is good practice to determine the manufacturer's range of values for ratio and RMS which are acceptable, as they will not always be computed in the same way. In many software packages the baseline selection will all be an automated procedure.

It is recommended that the following information supplied by the software is extracted from the baseline summary and quoted in a baseline processing section of a final survey report as three distinct QC parameters for each static or dynamic baseline solution accepted:

- RMS
- standard deviation of the baseline components
- ratio, for fixed integer baselines.

The manufacturer, type and version number of the baseline processing software should also be detailed in the survey report.

In control surveys, once baselines are successfully estimated and selected, loop closures should be computed around the geometric figure of the network as a further quality control check. This is a second key check to ensure baseline estimation has been correctly achieved. This check is of paramount importance when processing large numbers of baselines in batch jobs, as careful treatment of each baseline is unlikely to have been carried out. As a general rule, for closures of lengths between 10 and 50km, those exceeding 3ppm should be investigated. It should be noted that any misclosures left in the project will be propogated into the final co-ordinate error ellipses. Thus, if a specification requires final error ellipses to be better than 0.1m at 95 per cent, all misclosures of greater than 0.1m must be eliminated to achieve the specification.

Where a new single point has been observed with reference to a number of base stations, the co-ordinate recovery technique should be used. The source control point nearest the new point is treated as base station to compute the new point. Then, from the new point, baselines are computed out to the other source control stations. The difference between computed and published co-ordinates will give an indication of the accuracy of the result, highlighting dubious source control GNSS data.

7.5.6 Network adjustment

Following the GNSS baseline estimation within the baseline processing part of the software, GNSS vectors are generally passed to the network adjustment part of the software. GNSS vectors and the associated full covariance information should be passed across. However it should be noted that for float solutions, where the baselines are still biased by the non-fixed integers, the covariant elements may be discarded prior to network adjustment.

Within the network adjustment software there should be a capability to allow for different classes, or groups. This will allow different weighting strategies to be adopted for different classes of baseline solutions, or for different types of terrestrial observations. A combination of kinematic, rapid/fast static or static baselines can then be included, with properly ascribed significance, in a common adjustment. The combination of terrestrial observations with GNSS data is a complex field of study, and appropriate specialist combined network adjustment software should always be used by experienced personnel with substantial expertise if this is to be undertaken.

7.5.7 Network statistical testing and measurement weighting

Within a network adjustment the initial focus should be based around testing of the individual measurements. A procedure following the computation of standardised residuals and their comparison against a chi-squared probability test and the tau criterion is recommended, and should be included in any software. This may well take place as part of a preliminary, or free adjustment. Within this process it is recommended that only non-trivial (see section 7.2) baselines are used. This avoids the problems of mathematically modelling correlated measurements.

Failure of testing against the chi-squared probability test and comparison against the tau criterion may be either representative of inadequate covariant information from the GNSS processing stage, network geometry limitations or true measurement deficiencies. Failure of testing should promote more evaluation and testing of the network before finally deciding upon explicit rejection of measurements.

Once the final set of measurements have been tested and selected, the adjustment should proceed with the appropriate weighting strategy applied. This is a vital aspect of any network adjustment as the final output of the station error ellipses are dependent on the weighting strategy used. For example, centring and height errors should be entered. In addition, the stations selected as control should be held fixed at their defined values with their computed precision. It is best practice to carry out network adjustments in ITRS89 before any co-ordinate transformations are made.

7.5.8 Key parameters for reporting

There will be a host of statistical tests and quality control parameters presented by the software throughout the adjustment process: standard deviations of adjusted co-ordinates, station error ellipses, RMS figures, covariant values, histograms and observation residuals. From these, it is recommended that the most important quality control parameters extracted are the station error ellipses at the 95 per cent confidence level (check the sigma values given by the software) and the weighting strategy applied. These should be presented in the report in the following ways.

For each adjustment:

- the weighting strategy adopted including the a priori standard errors used
- the overall unit variance for the network (which should be approximately equal to one).

For each station (given in the ITRS89 co-ordinate system):

- latitude and the 95 per cent confidence value
- longitude and the 95 per cent confidence value
- ellipsoid height and the 95 per cent confidence value.

The manufacturer, type and version number of the network adjustment software should also be given in the final survey report.

7.5.9 Post-processed DGNSS surveys

The quality control measures outlined above in section 7.3.3 for real-time DGNSS surveys should also be computed for any post-processed surveys. Reference should again be made to the IMCA publication *Guidelines for the use of differential GNSS in offshore surveying* (www.imca-int.com/divisions/marine/publications/199.html). It is recommended that if post-processed and real-time data is to be combined in a particular project, some check points are taken in both the real-time as well as post-processed modes.

7.5.10 Co-ordinate transformations and projections

Transformation of the co-ordinates from the network adjustment can also be carried out almost automatically within the same software suite or it may be undertaken manually in a completely different manufacturer's software package. There are no real statistical confidence values that can be determined from transformation of co-ordinates, as often the transformation is a simple mathematical function; from one ellipsoid definition to another, and thence to a defined projection and local grid. Therefore, when transforming GNSS results from the network adjustment, the following quality control parameters should be supplied in the survey report:

- transformation technique used (Moledensky, Helmert, MRE – see section 6)
- numerical definition of the new and ITRS89 ellipsoids
- actual values of transformation parameters used
- source of transformation parameters, e.g. NIMA, self-generated, national mapping agency
- accuracy of transformation parameters (see section 6)
- projection technique used and the numeric definition of the projection
- manufacturer, type and version of software
- new co-ordinates and final accuracy values in local datum or projection.

7.5.11 Data management

All recorded data should be compatible with National Spatial Data Infrastructures (NSDIs).

New co-ordinates and final accuracy values in local datum or projection should be managed and maintained by surveyors in support of NSDI initiatives.

Appendix A: GNSS verification, testing and maintenance

GNSS receivers should be checked and maintained on a regular basis. The checks should be included in any quality assurance documentation. Testing and maintenance can be split into internal company checks and external manufacturer checks.

A1 GNSS verification (internal company checks)

See ISO standard 17123: Field procedures for testing geodetic and surveying instruments – GPS field measurement systems in real-time kinematic (RTK).

There is little that the average user can do to check the internal components of a GNSS system. However, baselines of a known length can be surveyed. These should be previously established test baselines, suitably adjacent to a company's offices. Most land survey companies should have access to a test baseline for EDM instruments. These will typically be a few points in a straight line over a total distance of 200m to 700m with differing internal distances.

Where these EDM baselines are suitable (see section 5), it is recommended that testing of GNSS receivers and ancillaries used for dynamic surveys is carried out. A base receiver may be established at one end of the test base. Roving receivers should then be set over each of the other baseline points. The GNSS-derived distance should then be compared with the internal distances measured using EDM. The manufacturer's tolerances and precision values for both the EDM and GNSS equipment should be taken into account during the comparison. Generally, results should compare to within the precision stated in **Tables D1 to D3** (p. 11), or to within the specific manufacturer's precision given for the GNSS system under test.

Land survey and equipment hire companies, who purchase or own static GNSS systems, are recommended to establish a GNSS test network. This should be a simple 5–10km baseline circuit of three or four interconnected baselines, with appropriately monumented stable control stations. This should be established when the receivers are first purchased. A static survey of several independent sessions, using different satellite constellations and different times of day should be carried out to fix the baselines. At least two stations in the circuit should have control co-ordinates to better than 1m absolute in ITRS89.

The high-precision static survey guidelines should be followed for GNSS receiver testing, using the network at intervals of typically six months. Receivers should be tested after firmware upgrades, or on return from a manufacturer's upgrade or repair. Post-processing software should be tested on archived data after a software upgrade or new release. Any differences exceeding the stated precision of the instruments or system should be reported to the manufacturer.

Ancillary survey equipment should be tested regularly – in particular tribrachs, adaptors and other centring equipment, as well as tapes or height rods, compasses and clinometers. If weather observations are made when using GNSS equipment, instruments such as barometric pressure recorders, wet/dry thermometers and humidity meters should be tested.

A2 Equipment testing (external manufacturer checks)

The manufacturer's advice regarding service intervals and firmware upgrades should always be followed when purchasing GNSS equipment. Receivers should always be upgraded to the latest applicable firmware/software versions. Receivers and antennas should be returned to the manufacturer when repairs are necessary.

It is good practice to register GNSS equipment with the manufacturer to ensure that software and hardware changes and revisions are kept up to date.

Appendix B: Information on receiver types

Unfortunately, there can be no up-to-date listing produced for GNSS receivers, due to the rapid progression of the GNSS industry. However, for a basic equipment type by category listing, **Tables D1 to D3** on pages 11–14, can be used as a guide.

One of the main problems with GNSS surveying is the lack of an agreed nomenclature for receivers and systems. The guideline therefore is to try and obtain from the manufacturer the type of product they are really selling and to place it in the categories explained in section 3, namely:

- static system
- dynamic system
- real-time dynamic system.

Publications such as *GPS world*, *Geomatics world*, *Engineering surveying showcase* or GIM (see Appendix C) often have one issue per year which contains a review of GNSS receivers, or a buyer's guide. It is recommended that independent sources such as these publications are consulted before purchasing equipment, or when ascertaining the type of GNSS equipment being offered by a manufacturer or hire company.

A further reference could be made to the US FGCC (Federal Geodetic Control Committee) accredited listing of GNSS receivers, for detailed specifics on GNSS receiver types and precision. Manufacturers often submit a test receiver to the FGCC, which is the main organisation in the USA for testing and accrediting GNSS survey equipment and hardware. It is recommended that before a receiver is purchased, the listing is inspected, or possibly the test report is obtained.

It is not appropriate for this document to list the most common and well-known receivers. The above publications and the reviews contained therein should be consulted to assess the most appropriate receivers for a particular type of survey.

Appendix C: Further reading

Reference texts

Bomford, G. *Geodesy* (4th edition), Clarendon Press, Oxford, 1980

Hofmann-Wellenhof, B., Lichtenegger, H., Wasle, H. *GNSS – Global navigation satellite systems: GPS, GLONASS, Galileo and more*, Springer-Verlag, New York, 2007

Iliffe, J.C. and Lott, R. *Datums and map projections for remote sensing, GIS and surveying* (2nd edition), Whittles Publishing, Dunbeath, 2008

Kaula, W. *Theory of satellite geodesy: applications of satellites to geodesy,* Dover Publications Inc, Mineola, NY, 2003

Leick, A. *GPS satellite surveying* (3rd edition), John Wiley & Sons, Chichester, 2004

Seeber, G. *Satellite geodesy, foundations, methods and applications* (2nd edition), Walter de Gruyter, Berlin, 2003

Van Sickle, J. *GPS for land surveyors* (3rd edition), CRC Press, Lincoln, US, 2008

The following periodicals carry regular features on GNSS and its use in surveying:

Geomatics world and *Engineering surveying showcase*: PV Publications and RICS Geomatics Faculty. (Occasional articles, equipment reviews, projects and new GNSS systems.)

GIM: GITC. (Occasional articles and reviews.)

GPS World: Advanstar Communications, USA. (News and applications of the GNSS, occasional survey-related articles, equipment reviews and buyers guides.)

The following academic papers can be termed benchmark papers and have marked the major developments and innovations in the use of GNSS in surveying:

Euler, H-J. and Landau, H. *Fast GNSS ambiguity resolution on-the-fly for real-time applications* article in *Proceedings of the 6th international Geodetic Symposium on Satellite Positioning*, Vol. II, Columbus, Ohio, 1992: pp. 650-659

Hatch, R. *Dynamic differential GPS at the centimeter level* article in *Proceedings of the 4th International Geodetic Symposium on Satellite Positioning*, Vol. II, Austin, Texas, 1986: pp 1287-1298: Official Documents Public Domain

Remondi, B.W. (1985) *Global Positioning System carrier phase: description and use* article in *Bulletin Geodesique*, Vol. 59: pp. 361-377

The following academic papers have been used as references in the preparation of this document:

Hopfield, H.S. *Tropospheric effect on electromagnetically measured range: Prediction from surface weather* data article in *Radio Science*, Vol. 6, No. 3, 1971: pp. 357–367

Schupler, B.R. and Clark, T.A. *How different antennas affect the GPS observable* article in *GPS World*, issue 199, Nov/Dec 1991

Other guidelines and best practice documents are also available such as:

Colorado Department of Transportation *Survey Manual* Chapter 3 ‘GPS/GNSS Surveys’. Available at www.coloradodot.info/business/manuals/survey/documents/chapter3/chapter3.pdf

IMCA *Guidelines for the use of Differential GNSS in Offshore Surveying,* UK Offshore Operators Association, Surveying & Positioning Committee, London, 1994

National Geospatial-Intelligence Agency (NGA) *World Geodetic System 1984 – its definition and relationships with local geodetic systems* (WGS84). Available at http://earth-info.nga.mil/GandG/publications/tr8350.2/wgs84fin.pdf

Royal Melbourne Institute of Technology (RMIT) *Surveying Using The Global Positioning System*. Available at www.rmit.edu.au/browse;ID=ohupmnjp6l21

FIG publication 49 – *Cost effective GNSS positioning techniques commission 5*2010, available at www.fig.net/pub/figpub/pub49/figpub49.htm

The following general information sources and associated links on the internet can be used to obtain further details on GNSS and its use in surveying (correct at date of publication):

www.esa.int/esaNA/galileo.html

www.fig.net – commissions 5 & 6

www.glonass-ianc.rsa.ru

www.gps.gov

www.gps.gov.uk – UK GNSS RTK system

www.navcen.uscg.gov/GPS/geninfo/ – GPS References

www.navcen.uscg.gov/gps/geninfo/gpsacro.htm – GNSS acronyms

www.ordnancesurvey.co.uk/oswebsite/gps

RICS guidance and professional information

All RICS official practice standards and guidance can be downloaded free of charge from www.rics.org/standards

RICS guidance notes

EDM calibration (2nd edition), 2007.

Boundaries: procedures for boundary identification, demarcation and dispute resolution in England and Wales (2nd edition), 2009.

Client specifications (available from RICS books – www.ricsbooks.com)

Vertical aerial photography and derived digital imagery (2nd edition), 2009.

Surveys of land, building and utility services at scales of 1:500 and larger (2nd edition), 1997.

Terms and conditions of contract for land surveying services (5th edition), 2009.

Client guides (guides for the lay professional, available from www.rics.org/mappp)

An introduction to terrestrial laser scanning – a guide to terrestrial laser scanning.

Reassuringly accurate – a client guide to calibration.

Scale – once it's digital isn't everything full size? A guide on not tripping up over step changes in scale.

Virtually right? – Networked GPS – a guide on aspects of cost effective networked GPS correction services.

Virtually level – a guide on the transition from the familiar benchmark to heighting using GPS.

Map projection scale factor – a guide on how to understand and avoid the potential dangers of scale factor.

Appendix D: Sample specification with specific GNSS clause

The following extract could be part of a sample survey specification, based on the RICS *Measured surveys of land, buildings, utilities – a guidance note for surveyors*.

The elements which are related to GNSS are detailed:

2.1 Control network

The surveyor shall establish plan control at a density sufficient to achieve the specified accuracies. The main survey stations shall be of stable construction. The surveyor should choose the most appropriate marker for each location.

The final survey grid shall be arbitrary but related to the national grid. A description of the grid system used shall be quoted on each survey plan or upon the index plan. The control stations shall also be connected to the national grid values. The maximum error ellipse at 95% shall not exceed 20mm throughout the main control network. For this survey GNSS co-ordinates are required for the control stations and static or fast static GNSS survey shall be used for the control network.

The survey report shall include copies of the control station sheets and a method statement describing the survey technique used. Copies of the final network adjustment report shall also be included.

2.2 Level network

The surveyor shall establish vertical control at a density sufficient to achieve the specified accuracy of less than 5mm. The main site control station may be linked to the national vertical datum using a static GNSS control survey. A principal control station shall also be levelled to a national control bench mark and the closure value stated.

Appendix E: Sample procedures relating to a GNSS survey

These sample procedures are based on a simple method statement which could be given for a basic GNSS survey of an open site area, for example a road bypass site, where GNSS might be used for the whole work.

Method statement – GNSS survey

1 Site work

1.1 Further to a site reconnaissance any existing survey control will be inspected for stability and marking.

1.2 New control stations shall be installed, marked and prepared on station description sheets in accordance with the specification. They shall be selected in GNSS friendly location – where there exists a clear view of the sky to minimise cycle slips, multipath and other interference. Markers shall be road nails or earth anchors, as appropriate to the surface in which they are installed.

1.3 The following equipment shall be used for this survey … (state manufacturer, model/type)

1.4 One GNSS base station shall be established at a central location in the survey area. This shall be in an area with an open view of the sky as described above in paragraph 1.2.

1.5 As required, national control station(s) shall be observed or downloaded (via RINEX) to connect the survey to the national grid system.

1.6 Roving GNSS receivers will be established at other control stations forming a network around the whole site. These shall log data in a static mode at a rate and duration to achieve the accuracy required.

1.7 For the detail survey Real Time Kinematic (RTK) techniques shall be used within the above control network.

2 Office work

2.1 All GNSS survey data will be downloaded to office computers.

2.2 Survey data processing shall be carried out in … (state name of manufacturer's software).

2.3 Prior to processing the control network, antenna heights shall be checked twice, once on import and once during set up of processing parameters. Baselines shall be processed and checked, loop closures shall be computed and a network adjustment shall be performed. Co-ordinates shall be output in the specified grid system with their precision values, together with a listing containing the full details of the transformation and parameters used.

Glossary

Almanac

A set of parameters transmitted by each GNSS satellite that enables a receiver to predict the approximate location of the satellite. The data includes orbit information on all the satellites, clock correction, and atmospheric delay parameters. This data is used to facilitate rapid SV acquisition. The orbit information is a subset of the ephemeris data, with reduced accuracy.

Ambiguity

The unknown integer number of carrier phase cycles in an unbroken set of GNSS measurements. In GNSS processing mathematical calculations are made to compute this number, thus 'resolving the ambiguity'.

Antenna swap

A method of initialisation of kinematic surveys.

Atomic clock

A clock whose precise output frequency is maintained using radio frequency (RF) energy emitted or absorbed in the transmission of atomic particles between energy states, resulting in a very stable clock reference. GNSS satellites carry either a caesium or rubidium clock and the master control station uses caesium and hydrogen master clocks.

Baseline

The three-dimensional vector distance between a pair of stations for which simultaneous GNSS data has been collected and processed with static differential techniques. This is the most accurate GNSS result.

Bias

See Integer bias terms.

C/A (Coarse/Acquisition) Code

Two pseudo random noise (PRN) codes are transmitted by each GPS satellite, C/A and P (Precision). C/A is the simpler, non-military code which is modulated onto the GPS L1 signal. The code is a sequence of 1024 pseudo random binary bi-phase modulations of the GPS carrier at a chipping rate of 1.023MHz, thus having a code repetition period of one millisecond. This code was selected to provide good acquisition properties.

Carrier

An unmodulated radio wave having characteristics of frequency, amplitude, phase.

Carrier frequency

The frequency of the unmodulated fundamental output of a radio transmitter. The GPS L1 carrier frequency is 1575.42MHz.

Chip

The length of time to transmit either a zero or a one in a binary pulse code.

Chip rate

Number of chips per second (e.g. C/A code = 1.023MHz).

CIO/BIH

Conventional International Origin/Bureau International d'Heure.

Clock offset

The difference in the time reading between a satellite clock and a receiver clock.

Code division multiple access (CDMA)

A method of frequency reuse whereby many radios use the same frequency but with each one having a separate and unique code. GPS uses CDMA techniques with Gold's codes for their unique cross-correlation properties.

Compass

The Chinese GNSS system.

Correlation-type channel

A GNSS receiver channel which uses a delay lock loop to maintain an alignment (correlation peak) between the replica of the GNSS code generated in the receiver and the received code.

Cycle slip

The loss of lock of the satellite signal by the receiver. When lock is resumed the fractional part of the measured phase would still be the same as if tracking had been maintained. The integer number of cycles exhibits a discontinuity or ‘cycle slip’.

Data set

The simultaneous data collected at two or more stations.

Delay lock

The technique whereby the received code (generated by the satellite clock) is compared with the internal code (generated by the receiver clock) and the latter is shifted in time until the two codes match. Delay lock loops can be implemented in several ways; tau dither and early-minus-late gating.

Differential positioning

Determination of relative co-ordinates of two or more receivers which are simultaneously tracking the same satellites. Dynamic differential positioning is a real-time calibration technique achieved by sending corrections to the roving user from one or more monitor stations. Static differential GNSS involves determining baseline vectors between pairs of receivers.

Differential processing

GNSS measurements can be differenced between receivers, satellites, and epochs. Although many combinations are possible, the present convention for differential processing of GNSS phase measurements is to take differences between receivers (single difference), then between satellites (double difference), then between measurement epochs (triple difference).

A single difference measurement between receivers is the instantaneous difference in phase of the signal from the same satellite, measured by two receivers simultaneously. A double difference measurement is obtained by differencing the single difference for one satellite with respect to the corresponding single difference for a chosen reference satellite. A triple difference measurement is the difference between a double difference at one epoch of time and the same double difference at the previous epoch of time.

Dilution of precision (DOP)

A computed unitless scalar value which describes the geometric contribution to the uncertainty of a GNSS position solution. For any GNSS fix a DOP value is computed. It is usually either geometric DOP (GDOP), position DOP (PDOP) or horizontal DOP (HDOP). In addition, other values exist such as vertical, time and relative DOP. See definition of PDOP for further details.

Doppler aiding

The use of Doppler carrier-phase measurements to smooth code phase position measurements.

Doppler shift

The apparent change in frequency of a received signal due to the rate of change of the range between the transmitter and receiver.

Double difference method

A method to determine that set of ambiguity values which minimises the variance of the solution for a receiver pair baseline vector.

Dynamic differential

See Differential (relative) positioning.

Dynamic positioning

Determination of a time series of sets of co-ordinates for a moving receiver, each set of co-ordinates being determined from a single data sample, and usually computed in real time.

Earth-centred earth-fixed (ECEF)

Cartesian co-ordinate system where the X direction is through the intersection of the prime meridian (Greenwich) with the equator. The axes rotate with the earth. Z is the direction of the spin axis.

EGNOS (European Geostationary Navigation Overlay Service)

A European operated, satellite based real-time differential GNSS system. EGNOS transmits a signal containing information on the reliability and accuracy of the positioning signals sent out by GPS and GLONASS.

Elevation

Height above a defined level datum, e.g. mean sea level or the geoid.

Elevation mask

The lowest elevation in degrees above the horizon at which a GNSS receiver is set to track a satellite. It is usually set to 10 degrees or 15 degrees to avoid atmospheric effects and signal interference. A lower mask angle would increase ionospheric distortion and also tropospheric effects.

Ellipsoid

In geodesy, unless otherwise specified, a mathematical figure formed by revolving an ellipse about its minor axis. Used interchangeably with spheroid.

Ephemeris

The set of data which describes the position of a celestial object as a function of time. The GNSS ephemeris is used in the processing of GNSS observations. Either the broadcast ephemeris from the satellite navigation message or a precise ephemeris calculated from GNSS tracking stations can be used, depending on application.

Epoch

A point in time which is the reference for a set of co-ordinates. The measurement interval or data frequency, as in recording observations every 15 seconds. In this example loading data using 30-second epochs means loading every other measurement.

ETRF (European terrestrial reference frame)

See Reference frame.

ETRS (European terrestrial reference system)

See Reference system.

Fast switching channel

A switching channel with a sequence time short enough to recover (through software prediction) the integer part of the carrier beat phase.

Fixed integers

See Integer bias search.

Float solution

A baseline solution that does not fix the integer ambiguity values to whole numbers. The values are left as non-integer real numbers giving the baseline a higher RMS. than a fixed baseline. In general float solutions are not acceptable as final baseline measurements.

Full wave

Term used to differentiate between measurements made with single-squared (codeless) and code-tracking receivers. Specifically, a receiver tracking L2 P-code can make measurement using the whole L2 wavelength (24cm): the full wave.

Fundamental frequency

The fundamental frequency used in GPS is 10.23MHz. The carrier frequencies L1 and L2 are integer multiples of this fundamental frequency. L1=154F=1575.42MHz, L2=120F=1227.60MHz.

Galileo

The European Commission's GNSS system.

Geocentre

The mass centre of the earth.

Geodetic datum

A mathematical model designed to best fit part or all of the geoid. Conventional datums depended upon an ellipsoid and an initial station on the topographic surface established as the origin of the datum. Such datums were defined by the dimensions of the spheroid, by the geodetic latitude, longitude and the height of geoid above the ellipsoid at the origin, by the two components of the deflection of the vertical at the origin, and by the geodetic azimuth of a line from the origin to some other point. Geocentric datums are designed to give the best possible fit worldwide rather than to depend upon values determined at an initial station. Their origin is the geocentre of the earth (see WGS 84 below).

Geoid

The particular equipotential surface which most closely approximates to mean sea level in the open oceans and which may be imagined to extend through the continents. This surface is everywhere perpendicular to the force of gravity.

Geoidal separation

Height of the geoid relative to the ellipsoid.

GDOP (Geometric dilution of precision)

The relationship between errors in user position and time and in satellite range. GDOP = PDOP + TDOP . See PDOP.

GLONASS

The Russian GNSS system.

GNSS

Global Navigation Satellite System (the generic term for satellite navigation systems, including GPS, GLONASS, Galileo and Compass).

GPS (Global Positioning System)

The United States GNSS system.

GPS-ICD-200

The GPS interface control document is a US government document that contains the full technical description of the interface between the satellites and the user. GPS receivers must comply with this specification if they are to receive and process GPS signals properly.

GPS week

GPS time started at Saturday/Sunday midnight on 6 January 1980 and the weeks are numbered from that date, up to 1024 weeks. The first week 'rollover', the start of the next renumbering, occurred on 21 August 1999.

Gravitational constant

The proportionality constant in Newton's Law of Gravitation is $G = 6.672 \times 10^{-11} m^3 kg^{-1} s^{-2}$.

Half-wave

Measurements made using L2 squared measurements. The squaring process results in only half of the original L2 wavelength being available, a doubling of the original L2 frequency.

HDOP (Horizontal dilution of precision)

See DOP and PDOP.

Height – ellipsoidal

The distance above or below the ellipsoid measured along the normal to the ellipsoid at that point. Not the same as elevation above sea level. GNSS receivers output position-fix height as the height above the ITRS89 ellipsoid.

HOW (Handover word)

The word is the GNSS message that contains time synchronisation information for the transfer from the C/A code to the P-code.

IERS

International Earth Rotation Service.

Initialisation

The moment when a rover GNSS receiver in a high precision real-time dynamic system (RTK) solves the integer ambiguity and gains a real-time high precision fixed baseline solution.

Integer bias search

The biases calculated in the float solution are fixed to integers. A search is then undertaken to find closely related sets of integers. These sets are compared to the initial set by dividing the sum of the squares of residuals of the trial set by that of the original set. A strong data set allows only one set of integers, and produces a ratio factor greater than 3.0. A weak data set may accept several different sets of integers with only small changes in its sum of the squares fit, thus producing a small ratio factor.

Integer bias terms

The receiver counts the radio waves from the satellite, as they pass the antenna, to a high degree of accuracy. However, it has no information on the number of waves to the satellite at the time it started counting. This unknown number of wavelengths between the satellite and the antenna is the integer bias term.

Integrated Doppler

A measurement of Doppler shift frequency of phase over time.

Ionospheric delay

The ionosphere is a non homogeneous (both in space and time) and dispersive medium. A wave propagating through the ionosphere experiences variable delay. Phase delay depends on electron content and affects carrier signals. Group delay depends on dispersion in the ionosphere as well, and affects signal modulation. The phase and group delay are of the same magnitude but opposite sign.

ITRF (International terrestrial reference frame)

See Reference frame.

JPO

Joint Program Office for GPS located at the USAF Space Division at El Segundo, California. The JPO consists of the USAF Program Manager and Deputy Program Managers representing the Army, Navy, Marine Corps, Coastguard, National Imagery and Mapping Agency (NIMA) and NATO.

Kalman filter

A numerical method used to track a time-varying signal in the presence of noise. If the signal can be characterised by some number of parameters that vary slowly with time, then Kalman filtering can be used to tell how incoming raw measurements should be processed to best estimate those parameters as a function of time.

Kinematic surveying

A dynamic method of GNSS surveying using carrier phase observations in which one receiver is moving and one receiver is stationary. It is a highly productive survey method, useful for ground control or camera positioning, but is sensitive to high DOP values, multipath interference and loss of signal lock. Operational constraints include starting from or determining a known baseline, and tracking a minimum of four satellites. One receiver is statically located at a control point, while others are moved between points to be measured.

L1 GPS frequency

The 1575.42MHz GPS carrier frequency used for the GPS system containing the coarse acquisition (C/A) code as well as the encrypted P-code used by the military. In addition, the L1 carrier contains the navigation signal used by commercial, non-military users.

L2 GPS frequency

A secondary GPS carrier frequency of 1227.60MHz containing only the encrypted P-code. This frequency is used in GPS surveying to calculate signal delays caused by the ionosphere.

L band

The radio-frequency band extending from 390MHz to (nominally) 1550MHz.

Mask angle

See Elevation mask.

Monitor station

Worldwide group of stations used in the GNSS control segment to monitor satellite clock and orbital parameters. Data collected here is linked to the master station where corrections are calculated and controlled. These data are uploaded to each satellite at least once per day from an upload station.

Multichannel receiver

A receiver containing many independent channels. Such a receiver offers highest signal to noise ratio because each channel tracks one satellite continuously.

Multipath errors

Signals can arrive at a GNSS receiver either by direct line of sight or can be reflected off nearby objects (hills, buildings, etc.), in which case the differences in path length will cause interference at the antenna and corrupt the pseudorange measurements and subsequent positional reliability. (An interference similar to ghosting on a television screen).

Multiplexing channel

A receiver channel which is sequenced through several satellite signals (each from a specific satellite and at a specific frequency) at a rate which is synchronous with the satellite message bit-rate (50 bits per second, equivalent to 20 milliseconds per bit). One entire sequence is completed every 20 milliseconds.

Narrow lane

A baseline solution that is a linear combination of the L1 and L2 frequencies. It is often an intermediate solution used for statistical testing in the process of obtaining a final L1 or iono free fixed solution.

NAVDATA

The 1500-bit navigation message broadcast by each satellite at 50bps on both L1 and L2 frequencies. This message contains system time, clock correction parameters, ionospheric delay model parameters, and the vehicles ephemeris and health. This information is used to process GNSS signals to obtain user position and velocity.

NAVSTAR

The name given to GPS satellites, built by Rockwell International, which is an acronym formed from NAVigation System with Time and Ranging.

Network RTK

The networking of GNSS base stations to enable real-time corrections to be generated and transmitted to users anywhere in the area covered by the base station network. Users receive GNSS corrections from a central source, not directly from individual base stations. The systems work by using the GPS observations at known network stations to model the unknown bias sources across the network area. From these, positional corrections can be generated and delivered to the rover as either a set of multiple reference stations or as the corrections that would be generated from a ‘virtual’ base station adjacent to the user. Actual raw base station GPS data or virtual GPS observation data is also transmitted to the rover.

Observing session

The period of time over which GNSS data is collected simultaneously by two ore more receivers.

PDOP (Position dilution of precision)

PDOP is a unitless scalar value expressing the relationship between the error in user position and the error in satellite position. Geometrically, for four satellites PDOP is proportional to the inverse of the volume of the pyramid formed by unit vectors from the receiver to the four satellites observed. Values considered good for position are small, say 3. Values greater than 7 are considered poor. Thus, small PDOP is associated with widely separated satellites. PDOP is related to horizontal and vertical DOP by $PDOP^2 = HDOP^2 + VDOP^2$. Small PDOP is important in dynamic surveys, which are sensitive to larger PDOP values, but much less so in static techniques.

Phase lock

The technique whereby the phase of an oscillator signal is made to follow exactly the phase of a reference signal. It does so by first comparing the phases of the two signals and then using the resulting phase difference signal to adjust the reference oscillator frequency, so as to eliminate phase difference when the two signals are next compared.

Phase observable

See Reconstructed carrier phase.

Point positioning

A geographic position produced from one receiver in a stand-alone mode. At best, position accuracy obtained from a stand-alone receiver is 20-30m, depending on the geometry of the satellites.

Precise (P)-code

The protected or precise code transmitted on both L1 and L2 GPS frequencies. This code is made available by the DoD only to authorised users. The P-code is a very long sequence (about 1014 bits) of pseudo random binary bi-phase modulations of the GPS carrier at a chipping rate of 10.23 MHz. It repeats every seven days but is a section of a full 37 week code. Each satellite uses a one-week segment of this code which is unique to each GPS satellite, and is reset each week.

Precise positioning service (PPS)

The full accuracy, single-receiver GPS positioning service provided to the United States military organisations and other selected agencies.

Pseudo random noise (PRN)

PRN is a sequence of binary digits that appear to be randomly distributed. This is used in the GNSS C/A and P codes, with each GNSS satellite transmitting a unique PRN. GNSS receivers use this PRN to identify which satellites they are tracking. The important property of PRN codes is that they have a low auto correlation value for all delays or lags except when they are exactly coincident. Each NAVSTAR satellite has its own unique C/A and P pseudo random noise codes.

Pseudo static

A technique involving the observation of two separate simultaneous data sets at two or more stations with a time gap between observations (60 minutes is recommended). Data sets can be computed with the kinematic processor or as a static GNSS observation set with two files at each station. Baseline vectors can be computed and applied to the known station(s) within a network. A good method when continuous lock is unlikely to be maintained due to vegetation or other obstructions.

Pseudolite

A ground-based GNSS transmitter station which broadcasts a signal with a structure similar to that of an actual GNSS satellite.

Pseudorange

The apparent distance from a satellite to the phase centre of a GNSS receiver antenna. This is computed from the C/A or P code which gives a signal propagation time. This time can then be multiplied by the speed of light to give an apparent distance, which is not the true distance.

Pseudorange differs from the actual range by the amount that the satellite and user clocks are offset, by propagation delays, and other errors. The apparent propagation time is determined from the time shift required to align (correlate) a replica of the GNSS code generated in the receiver with the received GNSS code. The time shift is the difference between the time of signal reception (measured in the receiver time frame) and the time of emission (measured in the satellite time frame).

Pseudorange difference

See Reconstructed carrier phase.

Ratio quality factor

See Integer bias search.

RDOP (Relative dilution of precision)

Multiplying RDOP by the uncertainty of a double difference measurement yields the spherical relative-position error.

Reconstructed carrier phase

The difference between the phase of the incoming Doppler-shifted GNSS carrier and the phase of a nominally constant reference frequency generated in the receiver. For static positioning, the reconstructed carrier phase is sampled at epochs determined by a clock in the receiver. The reconstructed carrier phase changes according to the continuously integrated Doppler shift of the incoming signal, biased by the integral of the frequency offset between the satellite and receiver reference oscillators. The reconstructed carrier phase can be related to the satellite-to-receiver range, once the initial range (or phase ambiguity) has been determined. A change in the satellite-to-receiver range of one wavelength of the GNSS carrier (19cm for L1) will result in a one-cycle change in the phase of the reconstructed carrier.

Reference frame

The realisation of any particular co-ordinate reference system by the measurement of points using survey instruments. There can be several realisations of any system as survey techniques and methods change.

Reference system

A mathematical definition of the particular co-ordinate system, including the origin, scale position and orientation of the reference ellipsoid.

Relative positioning

The process of determining the relative difference in position between two points with greater precision than that to which the position of a single point can be determined. Here, a receiver (antenna) is placed over each point and measurements are made by observing the same satellites at the same time. This technique allows cancellation (during computations) of all errors which are common to both observation sets, such as satellite clock errors, satellite ephemeris errors and the majority of propagation delays, etc. See Differential positioning.

RINEX (Receiver Independent EXchange format)

A set of standard definitions and formats to promote the free exchange of GNSS data and facilitate the use of data from any GNSS receiver with any software package. The format includes definitions for three fundamental GNSS observables: time, phase, and range.

RMS, RMSE (root mean square (error))

In general, when accuracies or tolerances have been specified, they refer to vector errors and are defined statistically as root mean square errors (RMSE), or as maximum tolerances. The RMSE is equivalent to a 67% tolerance, and a 90% tolerance is 1.65 times the RMSE when a representative sample of points is tested. Thus an RMSE of ± 0.01m indicates that in a representative sample of 100 points, it is expected that not less than 67 will be correct to better than ± 0.01m, and not less then 90 points will be correct to better than ± 0.016m. Any errors exceeding three times the RMSE, in this case ± 0.03m, can be regarded as mistakes.

Selective availability (SA)

A United States Department of Defense programme to limit the accuracy of C/A code GPS receivers to the 100m level. It introduced deliberate errors to the C/A code information and affected the satellite clocks. It can be switched on or off according to the current US Government policy. It was set to zero by Presidential Decree on 1 May 2000, but it is possible for it to be reinstated at any time.

Session

A period when data is collected simultaneously at two or more stations, numbered using the Julian day, i.e. 121-1 is the first session on Julian day 121.

Sigma (one sigma)

The 68th percentile or one standard deviation measure in a statistical population.

Simultaneous measurements

Measurements referenced to time frame epochs which are either exactly equal, or else so closely spaced in time that the time misalignment can be accommodated by correction terms in the observation equation, rather than by parameter estimation.

Slope distance

The magnitude of the three-dimensional vector from one station to another. The shortest distance (a chord) between two points.

Slow switching channel

A switching channel with a sequencing period which is too long to allow recovery of the integer part of the carrier beat phase.

Spheroid

See Ellipsoid.

SPP (Single point position)

An averaged GNSS position resulting from the processing of several consecutive minutes of autonomous GNSS position data at a single location.

Squaring-type channel

A GNSS receiver channel which multiplies the received signal by itself to obtain a second harmonic of the carrier which does not contain the code modulation. Used in so-called codeless receiver channels.

Standard positioning service (SPS)

The positioning service made available by the US Department of Defense to all civilian GPS users on a continuous worldwide basis, using the C/A code. The accuracy of this service is set at a level consistent with US national security. *See* Selective availability.

Static differential

See Differential (relative) positioning.

Static positioning

Positioning applications in which the positions of static or near static points are determined.

SV (Satellite vehicle)

Abbreviation used to indicate a GNSS satellite, followed by an individual identifying number. Also an abbreviation for space or satellite vehicle.

SV sync time

The epoch interval used on the receiver.

TDOP (Time dilution of precision)

See DOP.

TOW

Time of week, in seconds, from 0000 hrs Sunday GPS time.

Tropospheric (Tropo) correction

The correction applied to the measurement to account for tropospheric delay. This value is obtained from a model such as that of Hopfield.

Universal time

Local solar mean time at Greenwich Meridian. Some commonly used versions of universal time are:

- UT0 universal time as deduced directly from observations of stars and the fixed relationship between Universal and Sidereal Time; 3mins 56.555 secs;
- UT1 is UT0 corrected for secular change;
- UT2 is UT1 corrected for seasonal variations in the earth's rotation rate;
- UTC is Universal Time Co-ordinated; a uniform atomic time system kept very close to UT2 by leap second offsets. GNSS time is continuous and directly related to UTC. UTC – GNSS time = an interval with a magnitude of seconds, 13 seconds in 2002.

Update rate

GNSS receiver specification which indicates the solution rate provided by the receiver when operating normally. This would be expressed as a number of updates per second.

User range error (URE)

The contribution to the range-measurement error from an individual error source (apparent clock and ephemeris prediction accuracies), converted into range units, assuming that the error source is un-correlated with all other error sources.

VDOP (Vertical dilution of precision)

See DOP and PDOP.

Virtual RINEX

Network RTK systems can be employed to apply network correction information to the raw GNSS data to create Virtual RINEX observation files for locations anywhere within a GNSS network. The advantage of this is that during post-processing, baseline lengths between base station and rover are kept to a minimum, enabling greater accuracy.

WGS 84 World Geodetic System (1984)

The geocentric datum used by GNSS since January 1987. It has its own reference ellipsoid. WGS 84 is fully defined in publications by the US. National Imagery and Mapping Agency (NIMA).

Wide lane

A linear combination of L1 and L2 observations (L1–L2) used to partially remove ionospheric errors. This combination yields a solution in about one-third the time of a complete ionosphere-free solution.

Z-count

The GNSS satellite clock time at the leading edge of the next data sub-frame of the transmitted GNSS message (usually expressed as an integer multiple of six seconds).

Zero baseline

Collection of data by two or more receivers from the same antenna. Any relative baseline thus computed should be zero. It is used to check receivers at the start of tasks. (Warning: to avoid damage to the antenna, a special zero baseline DC block should be used.)

Checklists for GNSS survey specification and procedures

This page can be photocopied to assist in preparation of survey specifications and procedures. The client and surveyor should compile the information required for their respective sections, but also note the items contained in the other's checklist.

Client checklist

The appropriate RICS client specification guidelines can be used to write the overall survey specification. The following table can be used in addition, to ensure that specific GNSS related issues are addressed in the survey specification. It is likely that many surveying or mapping projects will include GPS as an element of the fieldwork and it is good practice to include GNSS survey guidelines for the surveyor within the specification at the outset.

GNSS related item to include in specification	Additional information	Check
Co-ordinate system requirements	Part 1 Section 3.4 Part 2 Section 6	
Final survey accuracy in plan and height	Part 1 Section 1.3 Part 2 Sections 4.2, 4.3, 4.4	
Number and type of survey control points required	Part 1 Section 1.2	
GNSS survey type (control/detail/positioning)	Part 1 Section 1.2	
GNSS products required	Part 1 Section 3.5	
GNSS survey method preferred (optional)	Part 1 Section 1.3 Part 2 Section 4	
GNSS equipment and software listing (optional)	Part 1 Section 3.5	

Surveyor checklist

When producing a set of procedures for any given survey or mapping task, it is recommended that details on the GNSS methods proposed by the surveyor are included. This will give the client confidence in the surveyors' understanding of the survey task and allow an assessment of their technical capability. The following table can be used as a checklist for the surveyor to prepare specific clauses within survey procedures that relate to GNSS issues. In all cases, it is the responsibility of the surveyor to ensure that the procedures written meet the specification of the client.

GNSS related item to include in specification	Additional information	Check
Confirmation of co-ordinate system and accuracy required	Part 1 Sections 1.3, 3.4 Part 2 Sections 4, 6	
Listing of proposed fundamental control points	Part 1 Section 1.2 Part 2 para. 6.3.5	
Confirmation of number and type of survey control points	Part 1 Section 1.2	
Confirmation of GNSS survey method proposed	Part 1 Section 1.3 Part 2 Section 4	
Statement of field and office procedures proposed	Part 1 Sections 3.2, 3.3 Part 2 Section 7	
Listing of proposed GNSS equipment and software	Part 1 Section 3.5	
Confirmation of products and reporting required	Part 1 Section 3.5	

Guidelines for the use of GNSS in land surveying and mapping

2nd edition, guidance note

This guidance note sets out best practice guidelines for surveyors and clients on the use of **Global Navigation Satellite Systems** (GNSS) in land surveying and mapping.

It provides the surveyor with a set of practical operational guidelines, which can be used when undertaking any survey that includes GNSS techniques. It also provides clients and purchasers of geospatial information generated from a GNSS survey with sufficient information to write a task specific specification for a GNSS survey. This sets out the accuracy requirements, final potential products and scope of work, from which the surveyor can produce an agreed specification and bid for a survey. This 2nd edition also deals with recent advances in GNSS capabilities such as commercially available RTK systems, SBAS and other augmentation systems, satellite constellation and its effects on precision and the effects of factors such as the troposphere and tidal loading.

The document is divided into two parts. Part 1 summarises the important criteria to be considered in GNSS surveying, and includes guidelines for best practice. Part 2 is a technical explanation which develops the themes of Part 1 in a more formal context. This is primarily intended for surveyors and clients who wish to understand some GNSS theory and the technical rationale behind the best practice guidelines. The document as a whole is a must read for all chartered surveyors who are interested or are already using GNSS/GPS technologies.

The following topics are covered:

- The role of GNSS in surveying
- The role of RTK and commercially available networks
- survey documentation
- survey operations
- survey methods
- Operational considerations
- Co-ordinate reference frames
- Quality issues

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