

Province of British Columbia (BC)

Guidelines for RTK GPS Surveys,

Including

Operating within a Municipal Active Control System

Area (BC ACS^m)



Integrated Land
Management Bureau

Version 1.2
November 2009

Table of Contents

LIST OF FIGURES.....	II
APPENDICES	II
1 INTRODUCTION.....	1
2 GPS RTK SURVEYS.....	1
2.1 RTK DESCRIPTION	1
2.2 RTK ACCURACY ISSUES	2
2.2.1 RTK Antenna Centering and HI Measurement	3
2.2.2 RTK Antenna Phase Center Movement	4
2.2.3 RTK Base Station Fixed 3D Coordinates	4
2.2.4 RTK Initialization	4
2.2.5 Satellite Geometry and Elevation Angles	6
2.2.6 Random and Short-Term Systematic RTK Errors	6
2.2.7 Radial Nature of RTK Surveys	7
2.3 RTK VALIDATION.....	8
2.4 RTK PRODUCTION SURVEYS.....	9
2.4.1 Horizontal Datums, Coordinates, and Projections	9
2.4.2 Vertical Considerations (Ellipsoidal Heights, MSL Elevations, Geoidal Undulations)	10
2.4.3 Planning and Preparation for an RTK Survey	10
3. MUNICIPAL ACTIVE CONTROL SYSTEMS: BC ACS^M.....	12
3.1. HISTORY.....	12
3.2. WHAT IS THE BC ACS ^M ?.....	14
3.3. BC ACS ^M COMPONENTS.....	14
3.4. BC ACS ^M ADVANTAGES	15
3.5 RTK CONTROL SURVEYS WITHIN A BC ACS ^M	15
3.5.1 RTK Antenna Centering and HI Measurements:	15
3.5.2 RTK Antenna Phase Center Movement:	16
3.5.3 RTK Base Station Fixed 3D Coordinates:	16
3.5.4 RTK Initialization:	16
3.5.5 Satellite Geometry and Elevation Angles:	16
3.5.6 Random and Short-Term Systematic RTK Errors:	17
3.5.7 Radial Nature of RTK Surveys:	17
3.5.8 Validations:	17
3.5.9 Horizontal Datums, Coordinates, and Projections:	17
3.5.10 Vertical Considerations (Ellipsoidal height, MSL elevation, Geoidal undulation):	18
3.5.11 Planning and Preparation for an RTK Survey within an Acs ^m :	19

List of Figures

Figure 1: Typical RTK GPS system setup.....	2
Figure 2: BC ACS Stations.....	13

Appendices

Appendix A	-	CRGB Documents
Appendix B	-	References
Appendix C	-	Recommended Information Sources

1 INTRODUCTION

This document provides guidelines for GPS Real Time Kinematic (RTK) surveys conducted within BC. Referrals to this document should be with the *British Columbia Specifications and Guidelines for Control Surveys Using GPS Technology*. It is assumed that the reader has an understanding of the GPS Control Surveys document *before* this RTK guideline document is read. Appendix B contains information links to obtain documents maintained by Base Mapping and Geomatics Services (CRGB) of the Ministry of Agriculture and Lands.

In these documents, it is assumed that static carrier-phase surveys are used for the reliable establishment of permanent survey control that will be fully integrated within the Provincial Geo-Spatial Reference (GSR). RTK techniques are suitable for topographic / detail / layout surveys, and can also be used for survey control establishment in support of specific projects. The accuracy expectation for RTK is typically a few-centimetres horizontal and perhaps 1.5 times worse in the vertical. Accuracy values are expressed at the 95% confidence level in this document.

Section 2 of this document describes general techniques and accuracy issues for RTK surveying.

Section 3 of this document describes the specific RTK application of working within a Municipal Active Control System area (BC ACS^m). The Capital Regional District (CRD), and the Metro Vancouver (MV) are example BC ACS^m operational areas. The High Precision Networks (HPN) established as part of the BC ACS^m initiatives are also discussed in this Section. Note that Section 3 is “generic” for RTK users working within a BC ACS^m. Operational details (e.g. current system configuration, data communication details, contact names, etc.) are available directly from the agency looking after each specific BC ACS^m.

2 GPS RTK SURVEYS

This Section describes GPS RTK surveys, including methodologies, procedures, errors, redundancy issues, etc. IMPORTANT NOTE: It is assumed that the reader has an understanding of the document: *British Columbia Specifications and Guidelines for Control Surveys Using GPS Technology*.

2.1 RTK Description

Real Time Kinematic (RTK) surveying is an advanced form of relative GPS carrier-phase surveying in which the Base Station transmits its raw measurement data to rover(s), which then compute a vector baseline from the Base Station to the rover. This computation is done nearly instantaneously, with minimal delays between the time of the Base Station measurements, and the time these are used for baseline processing at the rover (ideally a few seconds). The precision of RTK baselines can be almost as good as the precision of static carrier-phase baselines. If the Base Station coordinates are accurately known, this will usually result in accurate rover positions. The combination of fast and precise positioning, one-man operation, and wide work areas has resulted in RTK becoming an impressively powerful tool for some survey applications. Like other survey techniques, RTK does not solve every survey problem. RTK is only suitable for environments with reasonably good GPS tracking conditions (limited obstructions, multipath, and RF noise), and with continuously reliable communication from the Base Station to the rover.

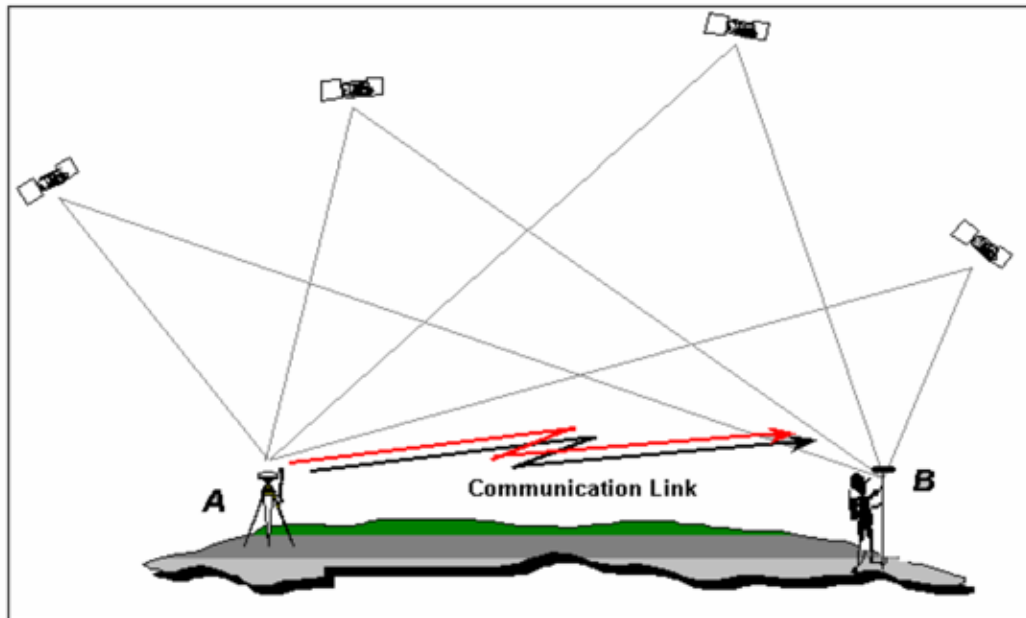


Figure 1: Typical RTK GPS System Setup

The above describes a typical RTK GPS System setup with one single Base Station supporting a rover within a working radius of the Base Station. The working radius is limited by 2 factors; the first being the data telemetry system communication range (not discussed here), and the second being the distance beyond which the RTK solution will not be reliable because the ionospheric and other distance-related errors begin to overcome the solution to the point where RTK initialization is no longer reliable. The effective working radius for a typical dual-frequency RTK GPS is usually quoted in the range of 10 to 20km.

The limitation described above has initiated the development of a network based RTK GPS, in which the data from an entire network of RTK GPS Base Stations is considered in real-time to allow fast and accurate rover initializations over a larger area. These techniques have been developing since the early 2000s, and the results look promising. Metro Vancouver (MV) and Capital Regional District (CRD) of southern BC have implemented such a network and have been very successful with their operation and usage. More information related to this service can be found at CRGB web site:

<http://ilmbwww.gov.bc.ca/crgb>

Future RTK implementations / refinements within BC will consider these developments, as well as the GPS modernization impacts of L2C and L5. Full deployment of GLONASS and GALILEO signals will greatly enhance the accuracy and productivity of RTK GPS activities also in the future.

2.2 RTK Accuracy Issues

The following Sections describe RTK-specific accuracy issues, and include suggestions to reduce their impact. REMINDER: General errors affecting carrier-phase GPS are discussed in the document: *British Columbia Specifications and Guidelines for Control Surveys Using GPS Technology*.

2.2.1 RTK Antenna Centering and HI Measurement

Static carrier-phase GPS surveys are usually done with antennas centered over the survey marks with precise tribrachs with rotating optical plummets / plate bubbles. Properly adjusted and used, this reduces the antenna centering error to < few mm. This is also the typical centering configuration for a dedicated RTK Base Station. RTK rover surveys are often done with the antenna mounted on a rangepole that is plumbed using a circular bubble. This is a less accurate centering method, and even a small error in the bubble can cause antenna centering errors of several centimeters. This may not be a concern during a topographic / pickup survey, but it would be for most control surveys. If the rangepole bubble is out of adjustment, it will lead to systematic horizontal errors. If the rangepole is oriented the same way for each measurement, it will increase the rover's random errors.

The antenna HI measurement must be accurate in order to reduce the solved 3D RTK solution to the survey marker or ground level. The vertical reference point for Height of Instrument (HI) measurement must be consistent with the manufacturer's procedures and software settings. Note that there may be many different antenna types available to use with each receiver, and each antenna type may have multiple vertical reference points that can be used for HI measurement. *This is an easy area in which to make a mistake.* Base Station antennas often have an extended ground plane or choke ring attached to the antenna, and this must be correctly selected in the RTK software. Base Station HI measurements are often done with a tape measure, or a dedicated HI measurement device. Rover HI measurements are usually directly made with the rangepole. Some rangepoles have adjustable top sections to accommodate different antennas or prisms, and this must be correctly set before the direct-reading rangepole heights can be used. A fixed-height rangepole (usually 2m) has the advantage that HI measurement errors are reduced, however, this type of rangepole does not allow the height flexibility of a telescoping rangepole (e.g. doing a topographic RTK survey in an area with 3m high vegetation). The higher the antenna height, the more susceptible it is to horizontal errors if the rangepole is not vertical. Two final notes regarding RTK antenna HI measurements are as follows:

- § if an incorrect HI is used at the RTK Base Station, all rover heights will be in error by the same amount
- § if an incorrect HI is used at the RTK rover, it may not be possible to initialize the integer ambiguities using the "known point" method.

The following suggestions are offered to reduce antenna centering and HI errors:

- All centering and HI measurement equipment must be kept in good condition, and must be checked / adjusted regularly.
- The best horizontal results will usually be achieved with the rover antenna set on a tribrach with rotating optical plummet / plate bubble.
- If a rangepole is used, consider mounting a 2nd circular bubble as a check for verticality (this will help detect if one of the bubbles is out of adjustment).
- A bipod / tripod should be used to steady the rangepole during survey control establishment.
- Rangepole centering errors can be minimized by observing each control point twice, with the rangepole rotated 180 degrees between observations. The average of the 2 positions should cancel any verticality errors.
- All measurements and software settings related to RTK antenna heights should be checked and verified. The heights should be measured in feet and metres to eliminate tape reading errors, and the values should be recorded manually in a field book for each practice. This applies both to the RTK

Base Station and to the RTK rover unit. Furthermore, the antenna types should also be manually recorded along with the vertical reference points on the antennas that were used.

2.2.2 RTK Antenna Phase Center Movement

RTK baselines are affected by Antenna Phase Center (APC) movements in the same way this affects static baselines. The optimal results are usually obtained by using the same antenna type, and the same antenna alignment at both the RTK Base Station and rover. If this is not possible, antenna modelling can be applied (as long as the models are consistent, i.e. generated by the same agency). Note that the exact antenna configuration must be known (e.g. with or without ground plane, choke ring, dome cover), and there must be a matching antenna model for this configuration before it can be used.

2.2.3 RTK Base Station Fixed 3D Coordinates

The computation of an accurate baseline vector (either static, or RTK) requires an accurate fixed 3D coordinates for the starting end of the baseline. With this scenario, if the errors in these established coordinates are large, than the baseline error is expected to be large as well. This impact is proportional to baseline length, therefore the shorter distances of RTK baselines are less affected than larger-scale projects with very long static baselines. Regardless, the RTK Base Station 3D coordinates should be carefully established in advance of the project. This is usually accomplished with redundant static baseline ties to existing survey control with appropriate horizontal *Network Accuracies*. The fixed ellipsoidal height is established in a similar way, with considerations for the vertical quality of the existing survey stations, and for the planned method of handling geoidal undulations on the project (see Section 2.4.2).

2.2.4 RTK Initialization

Similar to other carrier-phase GPS techniques, RTK requires the integer number of wavelengths between the receiver antenna and the satellites to be resolved in order to achieve the best baseline precisions (few cm). This is referred-to as the integer ambiguity problem, and if this is in-correctly computed, significant baseline errors can be induced without it being immediately obvious to the field operator. There are a number of approaches to solving the integer ambiguity problem when doing RTK surveys (often called RTK “initialization”).

- ***Known point initialization***

This initialization approach requires that the rover antenna be positioned over a point with accurately known 3D coordinates. This point can be an independent survey station that has been previously established, or it could be an extension of the RTK Base Station antenna setup via a short *initializer plate*. If using an initializer plate, care must be taken to ensure the alignment of the plate (usually via compass) is consistent with the specified initialization details. If using an independent survey station, the rover antenna centering and HI measurement must be carefully done. A known-point initialization allows the integer ambiguities to be directly computed with a few seconds of observations. The rover system should immediately perform statistical checking following the initialization, and show these results including a pass/fail indication. Initialization failure can be caused by incorrect 3D coordinates, miss-identified station, incorrect antenna centering or HI measurement, antenna movement during initialization, signal multipath, etc.

· ***Static Initialization***

This initialization approach requires the rover to remain stationary while the internal processor computes a static baseline solution between the Base and rover receivers. The required time for this type of RTK initialization varies from a few minutes, to over 1 hour (depending on the receiver type, separation distance, satellite geometry, etc.).

· ***On-The-Fly (OTF) Initialization***

This initialization approach allows the rover to be moving while the integer ambiguities are quickly resolved (typically within a few minutes). This technique is possible only with dual-frequency RTK systems, and it is successful only in areas that allow clear tracking of both frequencies. Manufacturers continue to improve the speed and reliability of OTF initializations, and this has had a significant impact on the practicality and feasibility of conducting RTK surveys. Some RTK systems continuously perform OTF initializations as an on-going quality check of the current initialization.

Regardless of the initialization method use, it is important to realize that the integer ambiguities may not always be correctly resolved. This issue may not be detected until some time has passed. Changing satellite geometry will usually indicate an incorrect initialization. Typically, the quality indicators gradually increase in magnitude until a threshold value is exceeded; then a flag is raised indicating a probable incorrect initialization. *Any survey work done during the interim period will have unknown accuracies, and should be confirmed before being accepted.* For this reason, it is important that the RTK field operator is aware of the initialization status at all times. Surveys that are conducted in areas with many tracking interruptions will be less reliable than surveys conducted in areas that are substantially clear of obstructions. During most RTK surveys, the field operator should attempt to maintain continuous GPS tracking for as long as possible (exception noted below).

A number of field practices have developed in order to improve the confidence in RTK initialization reliability:

- The survey work can be arranged in a series of loops to allow frequent repeat checks (redundancy). Temporary markers can be placed at appropriate locations and intervals, and these can be re-surveyed later and the 3D coordinates compared. If the comparison is within tolerance (typically a few cm), then this is normally a confirmation of a correct initialization. If the comparison is worse than expected, this is a flag for the field operator to be concerned about the initialization. Any survey work done with this initialization should be confirmed before being accepted.
- RTK systems with OTF capabilities can perform forced re-initializations as a check confirmation. This can be performed by inverting the GPS antenna (sometimes this operation is called an “antenna dump”) to force loss of tracking on all satellites. Then a new OTF initialization is done and the most recent point is re-surveyed and the 3D coordinates checked. This results in frequent checking of the rover initializations, however, it is still possible for systematic errors at either the Base Station or the rover to result in 2 separate initializations that are both incorrect. This field procedure results in only 2 points being surveyed with each RTK initialization, and there is some lost time during the frequent OTF waiting periods. This procedure does increase the reliability of all points that are checked with 2 separate initializations, although there is likely only a minimal accuracy gain due to the 2 back-to-back positions being computed from very similar GPS geometry.
- An extension of the above field procedure is to use 2 transmitting RTK Base Stations, and to survey all points with separate initializations from each Base Station. This improves the reliability, as some systematic errors at a specific Base Station (e.g. short-term multipath) would not be expected to be affecting the second Base Station at the same time. This field procedure produces 2 baselines connecting each surveyed point to the 2 Base Stations, and this will usually improve the network

geometric strength resulting in better accuracies. A second RTK Base Station also provides a blunder check of the fixed 3D Base Station coordinates used, and the HI measurements at each Base Station.

2.2.5 Satellite Geometry and Elevation Angles

In order to reliably resolve RTK ambiguities and work effectively, a minimum of 5 common tracked satellites is required. The geometric constellation of the satellites must also be suitable for the planned work. Tests conducted within the CRD BC ACS^m indicate that satellite geometry has an impact on the reliability and the amount of time required for RTK initialization. These tests showed some correlation between satellite geometry and RTK positional accuracies (as long as the correct initialization was obtained).

The geometrical strength of the GPS satellite constellation at a certain location and time are numerically represented using DOP numbers. Note that even though the PDOP, HDOP, and VDOP values actually indicate the geometric strengths for pseudorange, they can be considered an indication of the strengths for the respective baseline components as well. For simplicity, most RTK surveys consider just the 3D PDOP value. Good PDOP values are <3 , acceptable PDOP values range between 3 and 6, and a poor PDOP is >6 .

With good PDOP values, the ambiguity resolution is normally quick and reliable, and the instantaneous RTK positions are consistent. With higher PDOP values, the ambiguity resolution may take longer and become less reliable, and the RTK instantaneous positions may fluctuate more (although the mean of several epochs may still generate acceptable results). With poor PDOP values, a successful ambiguity resolution may not be achieved, and the poor geometry does not allow a reliable initialization check.

The satellite geometry can be predicted in advance using planning software. The instantaneous satellite geometry reflecting the actual satellites being used is shown on the RTK controller, and a mask value should be set to prevent working with poor geometry.

As satellites move close to the horizon, observation errors become unstable and more difficult to model. The errors are mostly due to the grazing path of the signal through the troposphere, and more susceptibility to multipath. Accepting measurements from low elevation angle satellites (e.g. <10 degrees) will result in a better theoretical geometry (more satellites available and lower PDOP values); however, the actual baseline results may be less accurate than if these satellites had been excluded. This is a trade-off that must be considered based on the surveyor's experience. It is suggested that an elevation mask of ~ 15 degrees be used initially, with a possible reduction later based on experience gained.

2.2.6 Random and Short-Term Systematic RTK Errors

RTK rover positioning can be done continuously while moving, or point features can be positioned with a short occupation (typically less than 15 seconds). All GPS observations are subject to random errors (e.g. receiver measurement noise), and short-term systematic errors can affect the observations (e.g. signal multipath, ionospheric disturbances, signal refraction through foliage, etc.). The quick nature of RTK surveys mean that these errors can influence the final positions more than during static carrier-phase surveys with much longer observation time-spans. The longer time spans reduce the impact of both random and short-term systematic errors, and this is why static carrier-phase surveys are used when the best results are required. A clear way to demonstrate this is to view the time-series plots of static carrier-phase residuals.

There is little that an RTK field surveyor can directly do to reduce the impact of random errors (short of observing for many minutes, and this defeat the purpose of a RTK survey). Some of the short-term systematic errors can be minimized by being careful with the antenna placement (avoiding nearby

multipath reflector surfaces), and possibly with receiver configuration settings (using a higher SNR mask to prevent foliage-refracted signals from being accepted, and raising the elevation mask to minimize troposphere & multipath errors). If it is possible and practical to re-occupy a station at a later time (e.g. using a different satellite constellation such as at least a 2 hours time difference), then a 2nd short occupation should improve the point accuracies, and it will improve the reliability through an independent occupation. If the two occupations show good coordinate agreement, both results can be combined to determine the final coordinate.

2.2.7 Radial Nature of RTK Surveys

The basic nature of RTK surveys results in a radial pattern of baselines extending from the Base Station to the surveyed points. This does not produce a strong geometric network, nor does it include survey redundancy for blunder checking and improved accuracies. This may not be a concern for some types of RTK surveys (e.g. topographic / detail pickup survey), but in other cases this radial network weakness may not be acceptable (e.g. control establishment survey). As an example, consider 2 control stations that are established within 100m of each other as an inter-visible pair for a conventional survey extension. If these stations are established relative to an RTK Base Station that is 15km away, the errors in these long baselines may result in poor *Local Accuracy* between the 2 control stations. By comparison, a well-designed static carrier-phase survey would include a direct baseline measurement between the 2 stations resulting in high *Local Accuracy*.

There are a number of approaches to improve the radial weaknesses of RTK surveys:

- If a 2nd Base Station is used, 2 baselines can be formed to each surveyed RTK point. This will improve the positioning reliability, and may improve the network geometry as well. It may be possible to form the 2nd baseline post-mission as long as the rover and the 2nd Base Station are recording raw observations (this means the 2nd Base Station does not have to be transmitting). *Note: There must be enough data to resolve the integer ambiguities.*
- If a 2nd RTK rover is coordinated to observe simultaneously, it may be possible to form rover-to-rover baselines post-mission. This would result in improved *Local Accuracies* from the direct baseline between the 2 points. This approach requires careful synchronization between the rovers, and both must record enough raw observations to resolve the integer ambiguities.
- Conventional survey measurements (distance and height-difference) can be observed between the local stations as a check on the RTK results. These observations can be added to a network adjustment (as long as a compatible weighting scheme is used). Note that this approach is *not* a complete check, as the orientation (azimuth) cannot be conventionally checked between a pair of local points (unless solar / star shots are done). If the conventional survey traverse commences on a pair of local stations, and terminates on a different pair, there will be a network-wide orientation check. This is a stronger and more reliable approach than a traverse that commences and terminates on the same station pair.

2.3 RTK Validation

The issues described in the previous Section have described the realities of an RTK system, and why it will not always produce accurate results. This is not intended as a negative statement to discourage RTK use; rather, it is presented for awareness, and to encourage a better understanding of the technology in order to achieve success with this powerful survey tool.

An important way for users to build understanding and confidence with RTK is to perform system validations. These RTK survey validations can be conducted on a network of stations that the user has established (e.g. a static carrier-phase network). Alternatively, the validations can also be performed on an external network of existing stations. For example, the GPS validation networks on the lower mainland and in the Okanagan, BC area (permanent concrete pillars with forced-centering), or other high accuracy survey stations from the MASCOT database. This network becomes the standard for comparing 3D coordinates from RTK validations. If RTK is considered for production vertical surveys, a careful validation should be performed to confirm the configuration necessary to meet the target vertical accuracies.

RTK validations should be conducted using a complete system that will be used for production surveys. This system consists of GPS hardware (receiver, antenna, controllers at the Base Station and rover), software / firmware (in the GPS receivers, field controllers, Antenna Modeling, and on the office computer), and support equipment (data telemetry system, antenna centering and HI measurement equipment, initializer plate, compass, etc). The field RTK surveyor and the office RTK data processor should be considered part of the system as well. Whenever a significant part of the system is changed, a new validation should be done. The following items highlight significant system changes that should trigger a new validation:

- Change of GPS receiver type
- Change of GPS receiver operating firmware that affects tracking or RTK processing
- Change of GPS antenna type
- Modification to GPS antenna (e.g. add/remove ground plane)
- Change of controller software that affects RTK processing (including a change of the APC Antenna Modeling)
- Change of office software that affects RTK processing
- Change of data telemetry system that affects transmission speed / throughput / initialization

An RTK validation should be planned to test / verify system performance under a range of conditions that replicate production surveys as closely as possible. The RTK accuracy issues discussed in Section 2.2 should be considered before planning a validation survey. The critical results to confirm with a validation survey are the initialization performance (reliability and time taken), and the positioning accuracy under various conditions. The following are some suggestions to include in an RTK validation.

- Base Station – rover separation distances ranging from near 0 to the maximum RTK working radius.
- Satellite geometry ranging good - acceptable - poor (e.g. PDOP <3, 3-6 , >6)
- Satellite elevation angle mask (e.g. between 10 and 15 degrees)
- Observing conditions ranging from completely clear to mostly obstructed
- Ionospheric stability (e.g. quiet, unsettled, active, storm)

There is no requirement for RTK systems to be formally validated by CRGB (unlike static carrier-phase GPS systems intended for the highest accuracy surveys).

2.4 RTK Production Surveys

The following Sections describe issues related to production RTK surveys.

2.4.1 *Horizontal Datums, Coordinates, and Projections*

RTK can be a fast and accurate survey method, but unless the results are consistent with the surrounding horizontal Geo-Spatial Reference (GSR), they may be of little value. Only a few projects are conducted on a purely local basis (i.e. with no external referencing).

There are a few basic definitions regarding horizontal referencing. GPS positioning derived from the broadcast ephemeris satellite positions are by default referenced to the GPS datum which is WGS84. The datum used in BC is NAD83. These 2 datums are similar, but not identical. WGS84 can be considered a space-based datum, whereas the NAD83 datum is realized by a network of defining survey monuments on the surface of the earth. The current realization is called NAD83(CSRS) (CSRS — Canadian Spatial Reference System), and it is based on a federal framework that is closely aligned with the highest-accuracy international reference frame (called ITRF — International Terrestrial Reference Frame). This NAD83(CSRS) datum extends within the province of BC via a massive re-adjustment of the control survey measurements in the MASCOT database constrained to the common federal framework stations. This province-wide adjustment was done in May 1998, with local areas being re-adjusted when new observations were subsequently made, and this is an on-going process.

RTK baselines are computed using the GPS broadcast ephemeris; therefore, these baseline vectors are referenced to the WGS84 datum. For RTK projects, the reference framework differences between WGS84 and NAD83(CSRS) can usually be ignored because of the relatively small extent of RTK projects (few tens of kilometers). This allows RTK baseline vectors to be considered as equivalent to NAD83(CSRS).

If the RTK Base Station is accurately referenced to NAD83(CSRS) the rover positions can be directly computed by adding the baseline vectors to the starting Base Station position. This method results in rover positions derived from baseline vectors radiating out from the Base Station. If the Base Station has good horizontal *Network Accuracy* (e.g. <2cm), and the RTK baselines have a typical accuracy of a few cm, this would result in rover positions with reasonable horizontal *Network Accuracies* (e.g. <5cm). This approach is considered correct for some types of RTK projects (e.g. topographic pickup survey). However, it would not be appropriate if the goal is to ensure the best integration within the surrounding GSR as defined by nearby monuments. The NAD83(CSRS) coordinates of these monuments will reflect localized survey distortions (e.g. from small errors in the survey measurements), but by definition, they define NAD83 (CSRS).

If the RTK rover positions are to fit within the GSR, and ensure good *Local Accuracies* between the new RTK positions and nearby existing stations, the survey design must include ties to the surrounding GSR. These ties may be from RTK observations, or for the best integration, they may be from longer-duration and more accurate static carrier-phase baselines. This results in creating a local calibration to fit the theoretical RTK network to the actual horizontal GSR. This calibration step may be done prior to the RTK project, or it may be done as the last step before generating the final results. If the local calibration is done first, it can be uploaded to the rover controller, and this will allow the display of final coordinates in real-time (e.g. allowing direct coordinate comparisons at existing monuments that are surveyed as a QC measure). The RTK local calibration must be done with careful consideration of the number, quality, and distribution of the available survey control. If poor quality control is selected (e.g. survey stations with poor *Network Accuracies*), or the distribution of control is unbalanced (e.g. local ties to the North & South, but no ties to the East or West), then the resulting calibration may actually degrade the final RTK results rather than improve them.

RTK projects may require the horizontal results be expressed as geographic coordinates (latitude and longitude), or they may be required as projected grid coordinates (e.g. UTM north and east). The transformations between Cartesian, geographic, and projected coordinates are usually a built-in function of the RTK software (both in the field controller and in the office software). If this is not available within the RTK software, a reputable utility software package should be used. Be aware that these transformations do not induce errors, but the derived results (e.g. areas, distances, azimuths) will produce different values depending on the coordinate-type used (e.g. differences between true and grid azimuths). Also, be aware that there will be a difference between horizontal results reduced to the ellipsoid, and results shown at ground level. If these concepts are not clear, a Geodesy text should be consulted (see references in Appendix C).

2.4.2 Vertical Considerations (Ellipsoidal Heights, MSL Elevations, Geoidal Undulations)

Similar to other GPS techniques, RTK requires special consideration when deriving MSL elevations from the native ellipsoidal heights. RTK users requiring accurate elevations should understand Section 2.2.7 of the document: *British Columbia Specifications and Guidelines for Control Surveys Using GPS Technology*.

The specific vertical *Local Accuracy* and *Network Accuracy* targets for an RTK project will guide the surveyor as to which of the 4 methods described in Section 2.2.7 of the above Document are suitable. Note that local RTK calibrations can be done 1D vertical, 2D horizontal (as described above), or 3D horizontal and vertical. If 3 or more well-distributed elevation points are included in a local RTK calibration, this is effectively creating a project-specific geoid model (the 4th method). This may be a valid approach on a small project area (e.g. few km extent), but it will lose accuracy on larger sites, or in areas with a convoluted geoidal undulation surface. Three elevation points allow the geoid surface to be represented as a sloped plane, but this has no redundancy / checking. Additional elevation points allow a higher-order polynomial surface, and/or redundancy.

Vertical RTK accuracies are generally lower than horizontal accuracies. This is caused by a number of factors including satellite geometry, atmospheric errors affecting the vertical solution, antenna phase center differences, geoidal undulation uncertainties, HI errors, etc. Some projects may have horizontal accuracy targets that are suitable for RTK, however the vertical project requirements may not be reliably achieved with RTK, and conventional leveling may have to be used instead.

2.4.3 Planning and Preparation for an RTK Survey

The following are planning and preparation suggestions in advance of RTK surveys (beyond the normal GPS carrier-phase planning issues such as the available satellite geometry taking into account any planned outages, ionospheric stability predictions, etc):

- The project site conditions should be reviewed with particular attention to obstructions that would limit satellite tracking (all quadrants except North). Difficult areas may have to be scheduled for particular times when the GPS coverage is suitable. The worst areas within the project may have to be surveyed using conventional techniques, in which case RTK may be used to establish local survey control stations near these areas. Alternatively, these stations could be established in advance by a static carrier-phase survey to gain better *Local Accuracies*, and they could be subsequently used during the RTK survey (initialization, check).
- The RTK Base Station must be established in a secure and stable location, with a good satellite tracking environment (minimal obstructions, and no nearby multipath reflectors or RF transmission antennas), and be suitable for RTK telemetry transmission to the project site. Accurate 3D

NAD83(CSRS) coordinates of the Base Station should normally be established in advance of the RTK survey. This is usually done by measuring static baselines to existing control stations that have appropriate *Network Accuracies*.

- Ties to existing survey stations (horizontal and vertical) may be required to ensure proper integration of the RTK project within the surrounding GSR (see Sections 2.4.1 and 2.4.2 above). These ties must be chosen based on their distribution, quality, and suitability for GPS tracking.
- The RTK telemetry system should be confirmed for reliable coverage across the project site. If the telemetry system is based on a dedicated radio modem, it may be possible to use repeaters to extend the coverage. In general, dedicated radio telemetry systems work best if the transmitters and repeaters are located at high points.
- The support equipment for RTK surveys (e.g. antenna centering & HI measurement aids, etc.) should be checked / adjusted before each project. This is critical if the RTK project includes establishing local survey control.
- The Antenna Modeling details must be confirmed (if the Base Station and rover are not using identical antenna types and configurations).

3. Municipal Active Control Systems: BC ACS^m

3.1. History

The Geo-Spatial Reference (GSR) unit is a part of Crown Registry and Geographic Base (CRGB) branch, Ministry of Agriculture and Lands, and the agency defines and manages, according to established standards and professional practices, the spatial coordinate system in the province to support geographic positioning activities. The GSR consists of two main components – a passive physical monumental system, and a satellite-based active positioning reference system. Both systems provide compatible universal coordinates to a myriad of government and private users.

The physical system consists of a network of over 50,000 survey control monuments situated throughout British Columbia. This network of monuments was established from mapping and control surveys conducted over the last century. Beginning in the 1960's, through a partnership between the provincial and local municipal governments, the physical control system was extended to developed areas (Integrated Survey Areas). The Geo-Spatial Reference unit maintains a provincial control survey database, called MASCOT, for the physical system. GSR also provides published coordinates and elevations for public access and use.

The GPS satellite-based reference system, known as the British Columbia Active Control System (BC ACS), has been providing province-wide coverage for post-mission differential GPS for surveying and mapping applications since 1996 via ~15 Active Control Points (ACPs) located throughout the province. The second phase of the BC ACS was realised in January 1998 with the launch of the Global Surveyor^m service providing real-time DGPS corrections across the province (code-based accuracies in the 1-10m accuracy range). The Global Surveyor^m service was replaced in October, 2003 by the wide-area system CDGPS (Canada-wide DGPS) providing 1-2m accuracies across all of Canada (and beyond).

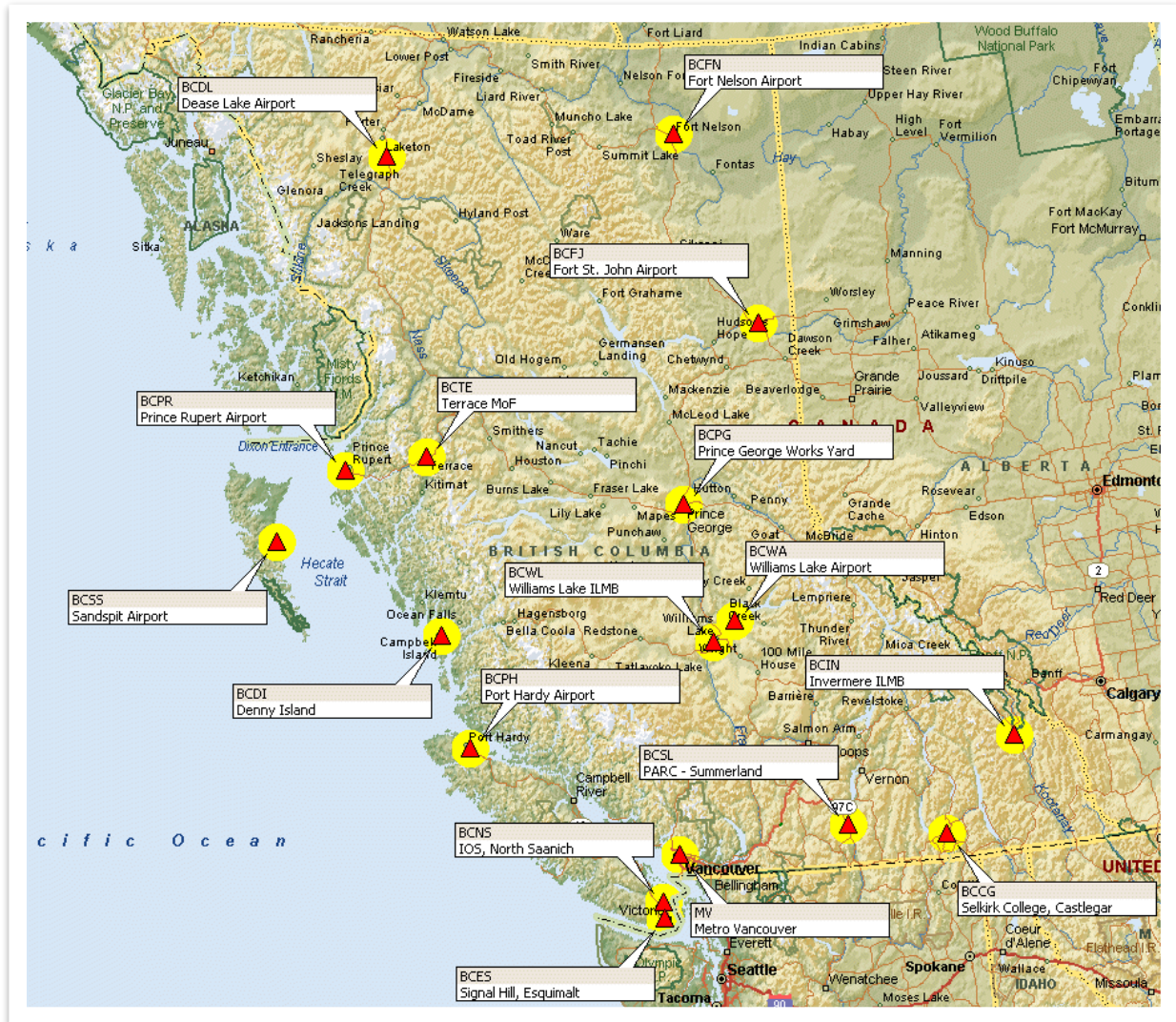


Figure 2: BC ACS Stations (October 2009)

The next phase of the BC ACS implementation develops a municipal-layer (BC ACS^m). The principal goal of the BC ACS^m is to establish a high accuracy and consistent real-time GPS-based geo-spatial referencing system to support Geomatics activities such as surveying & mapping, engineering and Geographic Information Systems (GIS). Furthermore, land information and socio-economic data management, precise vehicular location and navigation operations can benefit from the use of BC ACS^m that allows both public and private users to access a common, high accuracy active control system.

The first such extension of the BC ACS^m was realised in March 2001 with the launch of the Capital Regional District Municipal Active Control Area (BC ACS^m-CRD). Metro Vancouver (MV), its municipalities and the Province all collaborated for the implementation of the BC ACS^m-MV. The system is fully operational since 2005.

3.2. What is the BC ACS^m ?

Advances in GPS technology over the past few years have provided users with the ability to obtain few cm level positions in real-time via RTK techniques (see Section 2 above). This has enhanced the use of GPS by augmenting and replacing conventional surveying techniques.

The BC ACS^m is a system that provides post-mission and real-time GPS data that is rigorously integrated within the provincial GSR coordinate system. The system is designed with an open architecture to ensure that the data provided will be useable by all GPS end users (i.e. it supports all grades and manufacturer's GPS receivers).

Post-mission data is provided in RINEX (Receiver INdependent EXchange) format. RINEX is a standard format supported by all major GPS manufacturers, and includes code and carrier phase measurements for post mission processing.

Real-time data telemetry communication is supported via a wireless connection. The RTK Base Station data is transmitted using standard RTCM (Radio Technical Commission – Maritime) v3.0, v2.3 and CMR+ format. The RTCM format supports both code and carrier phase data enabling real-time rover positioning accuracies at the metre level (code), and at the few cm level (carrier-phase).

3.3. BC ACS^m Components

High Precision Network

An integral part of a BC ACS^m is the creation of a High Precision Network (HPN) of control stations that are tightly integrated within the provincial GSR. The HPN provides a 3D GSR with excellent *Local Accuracies* and *Network Accuracies* throughout the BC ACS^m coverage area. The HPN comprises a sparse network of control monuments (approximately 2km spacing) which are carefully surveyed using both a network of redundant static carrier-phase baselines, as well as precise levelling loops. The Active Control Points (ACPs) used as RTK Base Stations are directly integrated within the HPN, assuring a high level of compatibility between the passive physical control monuments and the active RTK system.

The HPN horizontal coordinate values are established by strong baseline connections to key framework stations, including ACPs, within the provincial and national GSR. This assures excellent horizontal *Network Accuracies* (typically <2cm). The dense network of baselines with all adjacent HPN stations directly connected results in excellent horizontal *Local Accuracies* (typically <1cm).

The vertical component of the HPN survey combines the ellipsoidal heights from the GPS network, along with the MSL orthometric elevations from the precise levelling (tied to provincial and federal benchmarks) to derive a local geoid model. This local geoid modelling will correct the surface to be applied on an existing published geoid model. The dense network of points allows good modelling of the geoidal undulations within the HPN, and this allows GPS-derived MSL elevations that are consistent with the HPN network stations.

Post-Mission Corrections

Active Control Points (ACPs), within the BC ACS^m, continuously track and record dual-frequency GPS data for post-mission applications. The GPS raw data is sent to the BC ACS Processing Master Active Control Station (PMACS) where it is processed and stored for subsequent download by end users. This data is available in 1 hour blocks via the Internet, usually with a delay of less than 3 hours.

Real-time Corrections

The GPS dual-frequency code and carrier-phase data at each ACP is transmitted to end-users in real-time. Proprietary software controls the GPS receiver operation, data logging parameters, and real-time data

transmission broadcast. Currently, each ACP transmits data independently. In the future, the data from all of the ACPs may be considered as an entire network before generating the real-time data transmissions.

The wireless data telemetry link details are specific to each BC ACS^m. In the CRD this is a dedicated UHF radio network of transmitters and repeaters. In the MV region, this is a cellular-based PCS system. The end user must arrange for wireless equipment and a network subscription before the system can be accessed. The specific details of accessing each system are described in the operational guides maintained by each municipal administrator.

3.4. BC ACS^m Advantages

The following are some of the advantages of working within a BC ACS^m as compared to working with a dedicated RTK system:

- **Fast, Easy & Secure:** All of the work and time required to set-up an operating RTK system has been done. Projects that may not have been worthwhile to do with a dedicated RTK system may be quick and practical to do within a BC ACS^m. Users do not have to worry about the security of their RTK Base Stations.
- **Accuracy:** The BC ACS^m is rigorously integrated within the provincial GSR at the highest accuracy level. Vertical MSL results are more accurate because of the comprehensive geoid modelling process across the HPN area. The high-accuracy HPN control stations throughout the BC ACS^m allow for RTK system initialization and checking while improving control for conventional surveys. The GPS receivers and antennas used as BC ACS^m Base Stations are high-quality, and are carefully sited to ensure accurate raw measurements.
- **Consistency:** Consistency is achieved with various different users accessing the same BC ACS^m system. The end-users may be public or private, the applications may be varied, and the rover equipment may be from different manufacturers, but the results will be consistent because the BC ACS^m framework is typically same and constant. This is important as more projects integrate information from a variety of sources.
- **Cost:** Dedicated RTK positioning requires at least 2 GPS receivers, plus a data telemetry transmitting system (including transmitter radio licensing fees). Working within a BC ACS^m reduces this requirement to 1 rover GPS system, plus a data telemetry receiver. This effectively halves the capital costs to perform RTK surveys. There are some operational charges (access fees) when working within a BC ACS^m, but these are more than offset by the reduced capital and operational costs when compared to a dedicated 2 receiver RTK system.

3.5 RTK Control Surveys within a BC ACS^m

This Section describes suggested procedures for conducting a local control establishment survey within a BC ACS^m using RTK techniques. These guidelines are designed for users wishing to establish local project control with positional accuracies in the range of 2 to 5cm. Other RTK survey applications will follow similar procedures, with appropriate modifications.

Most of the RTK accuracy issues described in Section 2 must be considered when working within a BC ACS^m (exceptions are noted below). These issues are reviewed in the context of performing RTK surveys within a BC ACS^m.

3.5.1 RTK Antenna Centering and HI Measurements:

The antenna centre and HI measurement can be considered free of any errors at the BC ACS^m Base Stations (the antennas are permanently mounted). Note that the antenna type and the HI vertical measurement point for the BC ACS^m Base Stations must be known and this must be set correctly in the

rover configuration parameters. This information is available in the operational guides maintained by each municipal administrator.

It is recommended that the RTK rover antenna be centred using a precise tribrach with rotating optical plummet / plate bubble when establishing survey control. Alternatively, a rangepole supported by a bipod / tripod can be used, however, care must be taken that the circular bubble is well adjusted, and a 2nd observation should be immediately done with the rangepole rotated 180 degrees. The results from these 2 back-to-back observations should be compared, and if they are within the expected tolerance, they should be combined (averaged) and this would be considered a single occupation of the control station. Rover antenna HI measurements should be carefully measured and checked, and manually recorded at each observation. A fixed-height rangepole will minimize HI errors and is preferable to a variable-height rangepole for control surveys.

3.5.2 RTK Antenna Phase Center Movement:

The antenna type and configuration (e.g. ground plane, choke ring, etc) must be known for the BC ACS^m Base Stations. This information is available in the operational guides maintained by each municipal administrator. If the rover and Base Station antenna types and configurations are identical, it is not necessary to apply Antenna Modelling during RTK baseline processing due to best possible RTK results. If the antenna types and configurations are not identical, Antenna Modelling must be applied during RTK baseline processing. It is critical that the Antenna Models applied are derived from the same source (e.g. both from the same equipment manufacturer, or both from the NGS).

3.5.3 RTK Base Station Fixed 3D Coordinates:

The fixed 3D coordinates of the BC ACS^m Base Stations are considered truthful. The published and broadcasted values should be used for all baseline computations.

3.5.4 RTK Initialization:

Any RTK initialization method is acceptable, as long as it is *checked* during the control survey. Note that the HPN stations offer a convenient network of high-accuracy points that can be used for a known-point initialization, and as an initialization check.

The following are options for checking an RTK initialization during control surveys:

- Compare 3D coordinates at an HPN station, while maintaining continuous tracking on with at least 5 or more satellites (e.g. no loss of initialization) before or after the control stations were established. The coordinate comparison should agree with the HPN published values within a few cm. It does not matter if this coordinate comparison is done before or after the control stations are surveyed, as long as the same initialization is maintained throughout.
- Repeat survey each control station with a new OTF initialization, and compare 3D coordinates. However, if a 2nd transmitting RTK Base Station is available, this should be used. If it is possible / practical to schedule the repeat survey for a later time (e.g. >2hrs to allow a different satellite constellation), this will improve the accuracy and reliability via an independent re-occupation. If using a rangepole, the repeat survey should be done with the rangepole rotated 180 degrees from the 1st occupation.

3.5.5 Satellite Geometry and Elevation Angles:

RTK control surveys should be performed with a minimum of 5 satellites, and with PDOP values less than 3. It is recommended that a satellite elevation mask of 15 degrees be used during control surveys.

3.5.6 *Random and Short-Term Systematic RTK Errors:*

Random RTK errors can be reduced by longer occupation times such as 30 seconds for each occupation, and by repeat surveys at a later time.

Some of the short-term systematic errors can be minimized by being cautious with the rover antenna placement. Control station should be set in a proper location to avoid nearby multipath reflector surfaces. Also using a higher SNR mask will prevent foliage-refracted signals from in the final solution.

3.5.7 *Radial Nature of RTK Surveys:*

The radial nature of RTK surveys is a weakness that must be considered when establishing local survey control. It is generally not acceptable to establish survey control with no redundancy (i.e. a single radial baseline from a Base Station). Suggestions to limit this weakness include:

- Repeat survey the control stations at a later time (>2hrs) to improve reliability and accuracy.
- Observe baselines from a 2nd Base Station either real-time, or post-mission.
- Simultaneously observe adjacent control stations with 2 RTK rovers, and process the inter-station baseline post-mission to improve the *Local Accuracy*, but not the *Network Accuracy*.
- Measure the inter-station distance and height difference with conventional survey equipment.
- Establish more than 2 control stations in each area to allow more comprehensive conventional checks.

Often more than one of the above techniques will be used to improve reliability and accuracy. Usually, 3 or 4 local control stations are established, repeat surveyed more than 2hrs later, plus comprehensive conventional checks are conducted.

3.5.8 *Validations:*

A BC ACS^m is an ideal environment for doing RTK system validations. The extensive HPN network allows validation checks at various distances from the Base Station(s), and with various tracking conditions. Every RTK system should be comprehensively validated at least once before it is used for production surveys in a BC ACS^m (see Section 2.3).

A project validation check should be performed immediately before starting an RTK control survey. This validation should be done with 1 or more HPN stations near the project site. After the rover is set up over the HPN station, and the RTK system is initialized, the solved 3D coordinates should be compared with the published values. Note that the heights should be compared, even if the control establishment project is only horizontal. If there is a significant discrepancy (e.g. > 5cm), this indicates an incorrect initialization, wrong rover parameters, or some other problem, it must be resolved before continuing. If the problem is not easily identified and fixed, it may be worthwhile to perform a check at a different nearby HPN station to prevent possible station disturbance or mis-identification. The 3D coordinate discrepancies will normally give an indication of the RTK performance under the current conditions (e.g. distance from the Base Station, current satellite geometry, ionospheric stability, etc). Note that this project validation check should be regarded as an indication, but not a guarantee, of the expected accuracies for establishing control survey stations. If it is possible to travel from the HPN station to the project site while maintaining tracking on at least 5 satellites, this also serves as a check confirmation of the RTK initialization.

3.5.9 *Horizontal Datums, Coordinates, and Projections:*

RTK survey projects done within a BC ACS^m will almost always be referenced to NAD83(CSRS), as defined by the high-accuracy HPN survey. This means that there is usually no need to distort the RTK

project to fit the local GSR via a calibration. This is a significant benefit of working within a BC ACS^m, and results in much higher coordinate consistency between different projects.

The final coordinates for the established local control stations will usually be the result of more than just single baseline vectors. The final result may be as simple as averaging the values from repeat surveys, or it may be a more rigorous least-squares adjustment including weighting from the baseline covariances. A significant benefit of a rigorous least-squares adjustment is the ability to review the observations via analysis of the residuals. Note that 2 RTK baselines observed back-to-back will have highly-correlated errors due to common satellite ephemeris and propagation errors, and this will tend to distort the overall adjustment statistics. To reduce this impact, repeat baselines should be observed with significantly different satellite geometry (e.g. >2hrs later).

The final coordinates will be expressed in the native format (Cartesian X, Y, Z or geographic latitude, longitude, ellipsoidal height). Furthermore, these coordinates can also be expressed as projected grid coordinates (e.g. UTM north and east). Some projects may require coordinates that are expressed at ground-level (rather than on the ellipsoid), and this requires the computation of scale factors representing the projection and the height above/below the ellipsoid. Projects that cover a small area (e.g. few km), and with relatively constant elevations, may use a single combined scale factor for the entire project. Other projects may require each station's coordinates be transformed to ground-level using projection and height scale factors computed specifically for each station. Ground-level coordinates, and the transformation method used, should be clearly identified so as not to be confused with the original ellipsoidal coordinates. Note that distances, orientation, and areas derived from coordinates will be different depending on what type of coordinates are used. If these concepts are not clear, consult a Geodesy text (see references in Appendix C), and/or consult a knowledgeable surveyor.

3.5.10 Vertical Considerations (Ellipsoidal height, MSL elevation, Geoidal undulation):

Similar to the horizontal discussion above, vertical surveys within a BC ACS^m have an advantage when compared to a dedicated RTK project done elsewhere. This is because the geoid modelling done as part of the HPN survey has pre-established the relationship between the GPS ellipsoidal heights, and the MSL orthometric elevations that are usually required for most projects. This geoid model is available from CRGB and/or the BC ACS^m municipal administrator, and its application is described in the operational guide.

Projects with a vertical MSL accuracy target of 5cm will likely be able to use the provided geoid model directly. Prior to production vertical surveys, the MSL accuracies should be confirmed on 2 or more HPN stations (or other stations with accurate spirit-levelled elevations) near the project site. If these checks shows a small but consistent bias (e.g. RTK-derived elevations always higher or lower than the published MSL elevations by a few cm), and all rover parameters have been checked and confirmed as being correct, then this small bias can be removed from the RTK results. This bias removal should be done after applying the BC ACS^m geoid model. If the checks show large and/or erratic discrepancies, the system parameters should be checked, and more HPN comparisons done until consistent vertical results are obtained. Note that the HPN geoid modelling process is comprehensive and extensive, and it is not expected that significant discrepancies will be seen within the BC ACS^m area.

Note that some projects such as layout or as-built surveys of water projects with shallow gradients, pavement construction and etc may not be suitable for RTK derived elevations. These projects are often done utilizing spirit-levels or construction lasers for vertical surveying. However, there is still value in configuring the RTK system to produce as accurate MSL elevations as possible, as this can be used as a coarse check for conventional blunders, even if the primary purpose for RTK is horizontal positioning.

3.5.11 *Planning and Preparation for an RTK Survey within an Acs^m:*

Some of the basic planning and preparation details discussed in Section 2.4.3 also apply for RTK surveys within a BC ACS^m are project site conditions, satellite availability, ionospheric stability, rover support equipment check / adjustment. Some other planning details are not required within a BC ACS^m would be set up of Base Station plus establishing accurate 3D coordinates, configuring a data telemetry system, horizontal and/or vertical calibrations to fit the existing GSR. There are a few planning and preparation details specific to working within a BC ACS^m :

- Access to the RTK data telemetry must be arranged, and coverage confirmed for the project area.
- Base Station(s) usually are selected to be closest to the project site).
- System configuration details must be obtained and confirmed as being current (e.g. Base Station antenna type and configuration, plus Antenna Modelling).
- Select the HPN station(s) to be used for a project validation

Support for RTK survey planning is contained in the operational guides for each specific BC ACS^m. These guides show the network configuration, data telemetry details, contact names and numbers, etc.

Appendix A

CRGB Documents

This section is intended to provide an overview of the various geomatics documents maintained by CRGB. These documents provide guidance for positioning in BC. Some of these documents are available on-line, and others are currently only available in hardcopy format. Most of these documents were revised and updated in recently. More information can be found at:

<http://ilmbwww.gov.bc.ca/crgb/gsr/specs/>

British Columbia Specifications and Guidelines for Control Surveys Using GPS Technology (rev. 2009)

This document includes detailed descriptions of GPS, and should be understood before reading the RTK document (this document). The focus is on carrier-phase GPS for accurate control surveys.

British Columbia Specifications and Guidelines for Control Surveys Using Conventional Survey Technology (ver. 2009)

As above, but for conventional surveys (e.g. optical total stations, spirit-levelling, etc).

British Columbia Standards, Specifications and Guidelines for Resource Surveys Using GPS Technology (ver. 2008)

This document is focused on Differential GPS applications with accuracy targets of 1-10m (typically for resource-sector surveys such as forestry, mining, etc).

British Columbia Guidelines for GPS RTK Surveys, including operating within a Municipal Active Control System area

The current document you are reading.

Appendix B

References

Accuracy Standards for Positioning (Version 1.0). Natural Resources Canada, Geomatics Canada, Geodetic Survey Division, Ottawa, ON. September 1996.

British Columbia Accuracy Standards for Positioning. Province of British Columbia, Ministry of Agriculture and Lands, Crown Registry and Geographic Base, Victoria, BC.

British Columbia Specifications and Guidelines for Control Surveys using Conventional Survey Technology. Province of British Columbia, Ministry of Agriculture and Lands, Crown Registry and Geographic Base, Victoria, BC.

British Columbia Standards, Specifications and Guidelines For Resource Surveys Using GPS Technology. Province of British Columbia, Ministry of Agriculture and Lands, Crown Registry and Geographic Base, Victoria, BC.

British Columbia Specifications and Guidelines for Control Surveys Using GPS Technology.. Province of British Columbia, Ministry of Agriculture and Lands, Crown Registry and Geographic Base, Victoria, BC.

GPS Positioning Guide. A Users Guide to the Global Positioning System. Natural Resources Canada, Geomatics Canada, Geodetic Survey Division, Ottawa, ON. January 1995.

High Accuracy Satellite Positioning. Course Outline. British Columbia Institute of Technology, Geomatics Department, Burnaby BC. March, 2001.

Standards and Guidelines for CADASTRAL SURVEYS Using Global Positioning System Methods (Version 1.0). United States Department of Agriculture – Forest Service, United States Department of the Interior – Bureau of Land Management, April 2000.

The Influence of the Number of Satellites on the Accuracy of RTK GPS Positions. Department of Land Information, RMIT University, Melbourne, Australia, June 1999. (As Published in the Australian Surveyor Vol. 44 No. 1).

GPS Antenna Calibration at the National Geodetic Survey. Gerald L. Mader, National Geodetic Survey, NOS, NOAA, Silver Spring, MD, USA, November 1999.

Analysis of Real-Time Kinematic and Fast Static/Kinematic Least Squares Derived Coordinates Using a Wisconsin County UDN. Paul Hartzheim, Darin Henkel, Wisconsin Department of Transportation, Presented at the Trimble User Conference, 1999.

Utilizing Real-Time Kinematic GPS for Control Surveys. Ronald E. Berg, M.A.Sc., O.L.S., Ministry of Transportation, Ontario Geomatics and Property Office, St. Catherines, Ontario, Presented at the Trimble User Conference, 1999.

Manual of Basic Computations using Universal Transverse Mercator Projection Co-ordinates Stored in the Crown Registry and Geographic Base Databank. Province of British Columbia, Ministry of Agriculture and Lands, Crown Registry and Geographic Base, Victoria, BC.

Appendix C

Recommended Information Sources

A Source for All Listed Materials:

Navtech Seminars and GPS Supply

6121 Lincolnia Rd, Suite 400
Arlington, VA 22312-2707, USA
Tel: 1-800-628-0885
Fax: (703)256-8988

<http://www.navtechgps.com>

Non-Technical Introductions:

Erickson, C. *GPS Positioning Guide*. Geomatics Canada, Natural Resources Canada, Ottawa. 1993.
An excellent, non-technical introduction to GPS. Emphasis on Differential GPS techniques.

Smith, J.R. *Basic Geodesy*. Landmark Enterprises, Rancho Cordova. 1988.
A very good introduction to the concepts of geodesy (including coordinate systems and datums), without the mathematical complexity behind those concepts.

Technical GPS and Geodesy:

Bomford, G. *Geodesy*. Oxford University Press, Oxford. 1980.

Hofmann-Wellenhof, B., Lichtenegger, H., and J. Collins. *GPS Theory and Practice*. Springer-Verlag, Wein. 1993.

Leick, A. *GPS Satellite Surveying*. Second Edition Wiley, New York. 1995.

Kleusberg, Alfred and Peter J.G. Teunissen (editors). *GPS for Geodesy (Lecture Notes in Earth Sciences)*. Springer, Berlin. 1996.

Wells, D.E., N. Beck, D. Delikaraoglou, A. Kleusberg, E.J. Krakiwsky, G. Lachapelle, R.B. Langley, M. Nakiboglou, K.P. Schwarz, J.M. Tranquilla, and P. Vanicek. *Guide to GPS Positioning*. Canadian GPS Associates, Fredericton. 1987.

Seeber, Gunter. *Satellite Geodesy* Second edition, Walter de Gruyter GMBH, Berlin. 2003.

Snyder, John P. *Map Projections - A Working Manual*. US Geological Survey, Washington. 1987.

Vanicek, P, and E.J. Krakiwsky. *Geodesy, the Concepts*. North Holland Amsterdam. 1986.

Torge, W. *Geodesy: An Introduction*. deGruyter, Berlin. 1980.

Krakiwsky, E.J. *Conformal Map Projections in Geodesy*. UNB Lecture Notes, University of New Brunswick, Fredericton. 1978.

Journals and Magazines:

GEO World Inc. (& related GEO magazines)

Tel: (312)846-4608

Fax: (312)846-4634

<http://www.geoplance.com>

GPS World

Tel.: (218)723-9417

<http://www.gpsworld.com>

GPS Solutions

Tel: (800) 777-4643

Fax: (201) 348-4505

<http://www.springer-ny.com>

Navigation, Journal of the Institute of Navigation

1800 Diagonal Road

Alexandria, VA 22314, USA

Tel: (703)683-7101

Fax: (703)683-7177

<http://www.ion.org>

Internet Sites of Interest:

Crown Registry and Geographic Base Branch, GeoBC:

<http://ilmbwww.gov.bc.ca/CRGB>

National Geomagnetism Program, Natural Resources Canada

Online Geomagnetic Activity Reports

<http://gsc.nrcan.gc.ca/geomag>

Geodetic Survey Division, Natural Resources Canada

Online geoid heights and NAD conversions

<http://www.geod.nrcan.gc.ca>

US Coast Guard Navigation Information Service

Official source of GPS information and NANU notices

<http://www.navcen.uscg.gov>

United States National Geodetic Survey, National Oceanic and Atmospheric Administration

GPS Antenna Calibration Results

<http://www.ngs.noaa.gov/ANTCAL>

University of New Brunswick, Fredericton,
Department of Geodesy and Geomatics Engineering
<http://gge.unb.ca>

University of Calgary, Calgary,
Department of Geomatics Engineering
<http://www.geomatics.ucalgary.ca>