Province of British Columbia

Specifications and Guidelines

For

Control Surveys
Using GPS Technology

BRITISH COLUMBIA
The Best Place on Earth
Integrated Land Management Bureau

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1. INTRODUCTION

The spatial coordinate system in BC is defined and managed by the Enterprise Spatial Services (ESS) – formerly Base Mapping and Geomatic Services (BMGS) and Crown Registry and Geographic Base (CRGB) – branch of the Integrated Land Management Bureau (ILMB). Traditionally this coordinate definition was provided through a passive network of geodetic control monuments spread throughout the province. Following the development of GPS, a satellite-based active reference system was implemented, known as the British Columbia Active Control System (BC ACS). Both the traditional passive network of monuments and the modern active GPS-based system are currently used for positioning.

The passive system consists of a network of over 50,000 control monuments throughout the province, connected with hundreds of thousands of survey measurements. These monuments were established for mapping and survey control projects conducted during the last century. Initially, most of these monuments were in remote locations; however, municipalities began establishing dense networks of survey control monuments in the 1960s. These municipal networks were built-up and maintained in partnership with the province.

BC ACS has provided province-wide coverage for post-mission GPS applications since 1996 via 15 permanent tracking stations. A second phase was realised in early 1998 with the launch of the Global Surveyor*tm* service providing real-time DGPS corrections across the province with 1-10m accuracies. In 2003, this service evolved into the Canada-wide Differential GPS (CDGPS) service providing improved real-time differential accuracies and much wider coverage (all of Canada and beyond).

The latter development of active referencing in BC was the high accuracy municipal networks called the BC ACS*m.* The principal goal of the BC ACS*m* is to allow consistent high accuracy GPS-based spatial referencing, in support of surveying, engineering, mapping, GIS, land information management, socio-economic data capture and management, and precise vehicular location and navigation operations. The first BC ACS*m* system was established in the Capital Regional District in 2002. Metro Vancouver service became operational in 2004. More information is available about these services at the following link:
http://archive.ilmb.gov.bc.ca/crgb/products/geospatial/bcacsm_MV.htm

As the active referencing systems became established and widely-accepted, the traditional passive system required less emphasis. It is recognized, however, that the physically monumented system is an essential spatial referencing system and popularly utilized across the province. Municipalities used to develop and maintain monumented survey control networks, however, in recent years, due to increasing cost and less usage, only disturbed monuments at important locations are deployed. Therefore specifications and guidelines are required in order to ensure that new monumentation are properly installed and integrated within the provincial spatial referencing system.

Use of GPS for survey control applications has influenced traditional monumented control networks. Station intervisibility has become less important, while an unobstructed horizon for clear satellite tracking is becoming more important. Modern survey instruments do not require the high-density of monuments that were established previously. Current municipal control networks are being designed with monument spacing of 800m or more.

Other GPS control projects being conducted for ESS include: High Precision Networks to support BC ACS*m* , GPS height transfers, and Geo-Referencing projects tied to the BC ACS. Each of these projects requires specifications and guidelines to ensure proper integration within the provincial spatial reference.

The accuracy of coordinates derived from GPS can be exceptionally good. Similar to other survey techniques, these accuracies can only be reliably achieved if the gross errors (blunders) and systematic errors (biases) are detected and removed. These specifications and guidelines are directed at the detection and elimination of gross and systematic errors.

GPS-derived elevations must be treated differently than conventionally-surveyed elevations. Conventional methods use orthometric elevations (also called Mean Sea Level or MSL) which are referenced to the Geoid, whereas GPS heights are referenced to the mathematical ellipsoid. The link between these 2 reference surfaces is the geoidal undulation, and special procedures are required when transforming GPS heights to orthometric elevations.

GPS surveying evolved with different "equipment and procedure" configurations capable of performing satisfactory GPS surveys. This makes it difficult and impractical to set rigidly defined specifications. The intent of this document is to not restrict contractors to specific equipment and procedures, but instead to take full advantage of present and future GPS capabilities. As a result, these GPS control specifications emphasis a rigorous system validation and comprehensive reporting approach, rather than specifying rigid design and field procedures.

The contractor’s GPS system is to be validated by demonstrating the ability to perform surveys to a specific accuracy level. This involves testing the contractor's equipment, field and office procedures, software, and personnel on a validation basenet. ESS analyses the contractor's validation submissions to determine if they have met the required accuracy standard(s). If the validation is successful, the contractor is then qualified to use this system to perform the specified types of control surveys.

Although strict specifications are de-emphasized for design and field procedures, they are not done away with completely. Instead, guidelines are included, and these will be updated as GPS technology becomes available and is applied. This document is intended to provide the contractor with a reference for successfully completing GPS control surveys, and also to give ESS the information necessary to evaluate and confirm the contractor's results.

Although each recommendation has been carefully reviewed, some have not been explicitly tested. GPS technology and application methods improve concurrently, and therefore some of these specifications may be considered preliminary or even dated. This document should be considered ‘live’, and refined as more experience and popularity is gained with GPS control surveys, and more feedback is received.

Specifications in this document fall into three categories: requirements, recommendations and suggestions. Each of these categories are identified by the following words:

shall or must	indicate a requirement that must be met by the contractor.
should	indicates a recommendation to be taken under consideration which, in the view of ESS, is necessary to achieve the required results.
may	indicates a suggestion which is left to the discretion of the contractor.

As a reference note that applies to this document; currently the term *GPS* only applies to the US Defence owned satellite navigation system. In the recent years, this expression is replaced mostly by GNSS (Global Navigation Satellite System). GNSS terminology includes US owned *GPS*, Russian Federation owned *GLONASS*, European Union owned *Galileo*, China owned *COMPASS* and all other proposed satellite based navigation systems. During the second revision of this document, only GPS is considered fully operational and GLONASS is regarded as a complementary system to increase field productivity and precision (under certain circumstances). Nearly all navigation system manufacturers have integrated GNSS compatibility within their hardware and users now have the option to employ GNSS or not in their daily field work. ESS will review the impact of additional GNSS satellites and include it in this document as necessary.

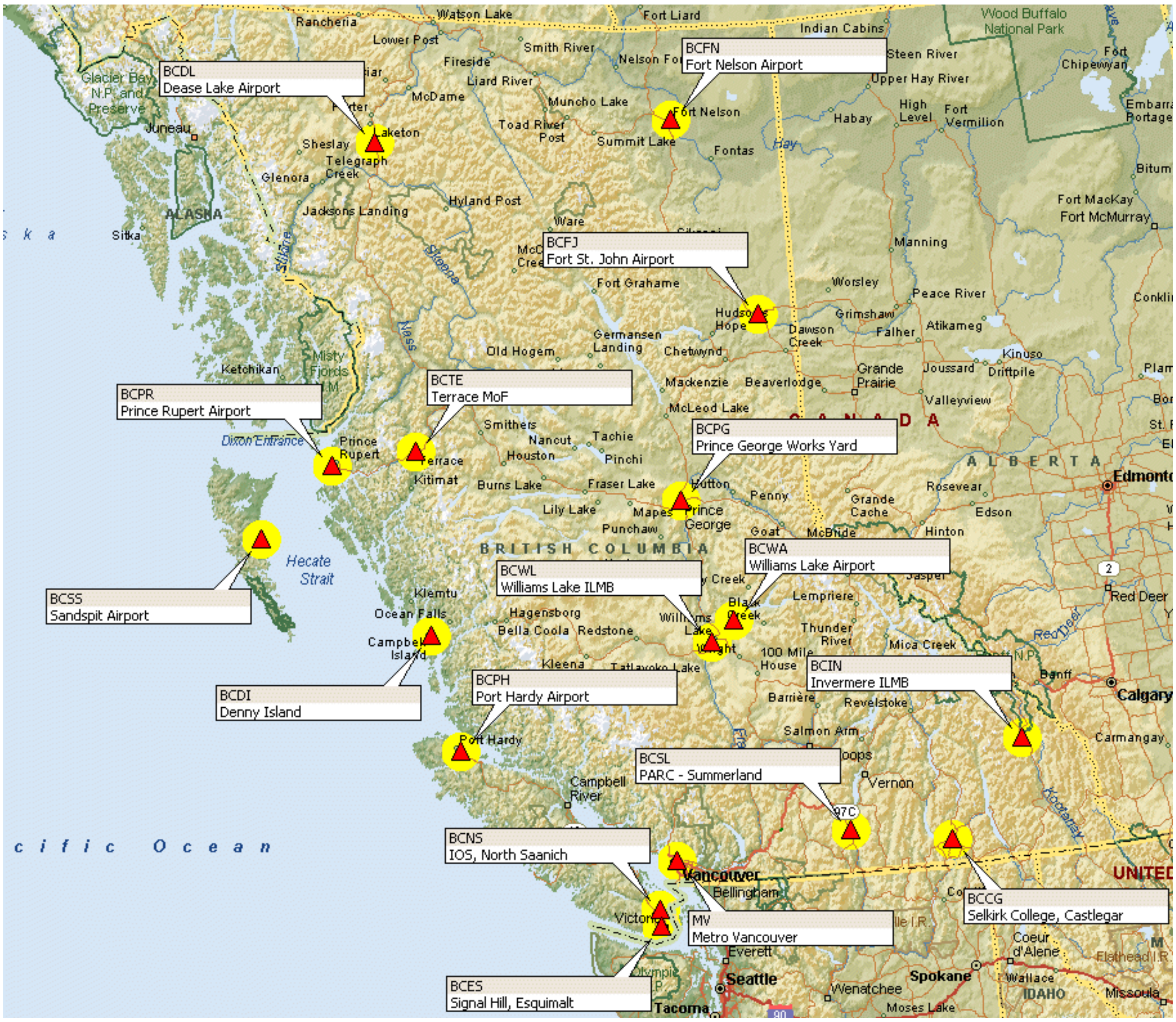


Figure 1- Current BC ACS stations across BC

2. GPS DESCRIPTION

2.1. GPS OVERVIEW

The Global Positioning System (GPS) is a US military satellite-based radio navigation system that can provide continuous, accurate and instantaneous positioning anywhere on or above the earth. GPS evolved from earlier satellite navigation systems of the 1960s and 1970s. The first GPS satellites were launched in 1978 and gave limited coverage during the initial development years that followed. Commercial receivers became available in the early 1980s and the civilian use of GPS began modestly, gathered momentum as new measurement techniques were invented and refined, and has since exploded to the level where civilian users far outnumber military users. The space shuttle Challenger disaster of 1986 setback the GPS launch programs, and it was not until 1993 that the system was declared IOC (Initial Operational Capability). The system was declared FOC (Full Operational Capability) as of December 12, 1995.

GPS is best understood by describing the 3 major segments that make up the system: the *space segment*, the *control segment* and the *user segment*. The following paragraphs give a general overview of GPS; more specific information is contained in later Sections of this document.

The *space segment* consists of at least 24 satellites at an altitude of ~20,000km above the surface of the earth, with an orbit period of ~12 hours. The satellites (also called Space Vehicles or SVs) are arranged to optimize coverage so that at least 4 satellites are visible at all times from anywhere on earth. Each satellite contains atomic frequency standards (clocks) that are extremely precise and this allows them to remain synchronized with other GPS satellites and also with the ground control system. All satellites broadcast at the same frequencies, but each has unique PRN codes (Pseudo Random Noise) that identifies a particular satellite and allows the user's receiver to make time-based distance measurements to each satellite. Each satellite also broadcasts the data elements necessary to compute the position of that satellite within its orbit at the exact time when the corresponding distance measurement was made. These data elements are called the ephemeris message.

The *control segment* consists of monitoring stations continuously tracking GPS at various locations around the earth, plus a master control station in the USA. The control stations monitor satellite performance, determine their individual orbits, model the atomic clock behaviour, and inject (upload) each satellite with their broadcast data (including the ephemeris message).

The *user segment* includes any user equipped with a receiver using GPS signals for positioning. In the basic mode of GPS operation (called pseudoranging), the user's receiver shifts a replica of each PRN code into alignment with the incoming signal from the satellites, and by scaling this time shift by the speed of light determines a distance (range) to each satellite. However, because the user's receiver is not precisely time synchronized with the GPS system, this time-based range is corrupted by an unknown amount referred to as the "range bias" or "user clock offset" (this is why this mode of positioning is called *pseudoranging* (*pseudo* means false) rather than simply ranging). With four pseudorange measurements, combined with the satellite positions from the ephemeris messages, the range bias can be computed along with the 3 dimensional coordinates (latitude, longitude and height). In most cases it is only the position that is important to the user, and the computed range bias is ignored. If more than 4 satellites are tracked, the user's position accuracy can be improved by using all measured pseudoranges in an over-determined solution. This basic mode of positioning is called *autonomous* or *single-point* as it is based on a single GPS receiver operating independently. This basic mode of positioning is typically used for general navigation (e.g. recreational use with a handheld GPS receiver), and provides an accuracy that is usually <10m. The nature of this autonomous positioning means that system errors may not be detected by the user, and therefore it is labelled as having *low positional integrity.*

The low positional accuracy and integrity of autonomous GPS drove the development of other GPS techniques more suitable for mapping and surveying. One development is *Differential* GPS (DGPS) based on improving the positional accuracy and integrity via relative pseudorange measurements from continuously tracking reference stations (also called base stations). DGPS techniques have high positional integrity because the measurements are checked at the reference station, and additionally, the positional accuracies are improved to <1m or less (depending on equipment, tracking conditions, etc). DGPS is a robust technique that is widely applied to resource mapping and surveying projects, and is described in the parallel document: ***British Columbia Standards, Specifications and Guidelines for Resource Surveys Using Global Positioning System (GPS) Technology.*** Please refer to ESS's specifications page at: **http://archive.ilmb.gov.bc.ca/crgb/gsr/specs**

A second development of GPS techniques is based on making measurements of the phase of the carrier waves (rather than tracking the PRN pseudorange codes). These carrier-phase techniques result in the best GPS precisions, and they have become the standard method for survey control establishment. Static carrier-phase techniques are based on continuous phase measurements tracked and recorded at multiple static receiver stations, which are then processed together post-mission using software to form interferometric differences. This results in precise relative *baselines* (3 dimensional coordinate differences) between each receiver-pair. The amount of carrier-phase data needed for precise and reliable results depends on factors that include satellite geometry and the length of baseline, with time periods of 30 - 120 minutes of static observations being typical. The precision of these measurements vary from a few millimetres to a few decimetres. GPS receivers that can track and record accurate carrier-phase observations are classified as *geodetic* instruments.

Receivers that can track both the L1 and L2 GPS frequencies can take advantage of the *wide lane* technique (a numerical combination of carrier-phase measurements on the two frequencies) to make precise static baseline measurements with shorter occupation times (e.g. 5-15 minutes within a localized area). This technique is called *Rapid Static* or *Fast Static*. Dual-frequency receivers also have an accuracy advantage for long baseline measurements (>10km) as the ionospheric signal delays can be directly measured and applied (see Section 2.2.2 for ionospheric information). This is not possible with single-frequency receivers tracking just L1. Both single and dual-frequency baseline measurements can be adversely affected by fluctuating ionospheric conditions during geo-magnetic storms.

Static phase techniques soon developed into kinematic phase solutions with centimetre-level accuracies possible instantaneously, even while moving. Kinematic solutions require an initialization process to resolve the ambiguities, and the receiver must maintain phase-lock on at least 5 satellites. The original methodology for kinematic surveys was post-mission, but this quickly evolved into Real-Time Kinematic (RTK) with the addition of a data telemetry link between the RTK base and rover receivers. RTK can be a very productive and precise methodology in the right project environment. Kinematic solutions are best suited for project areas that are substantially free of obstructions. Carrier-phase techniques do not apply to under-canopy surveys.

The remainder of this document deals with carrier-phase GPS techniques.

2.2. GPS CONTROL SURVEY ACCURACY ISSUES

The following Sections describe GPS issues that can affect the accuracy of carrier-phase surveys. These Sections are organized with a top-down approach (i.e. beginning at the satellite, and ending in the office). As with other survey methods, GPS errors can be categorized as random, systematic or gross. The objective is to prevent systematic and gross errors from influencing the survey results.

2.2.1. SATELLITE ERRORS

Satellite Ephemeris

Errors in satellite positions caused by an inaccurate ephemeris can induce errors in the computed baselines. The relationship between ephemeris errors and baseline errors is variable depending on the satellite geometry, and the error impact is related to the baseline length (e.g. long baselines are more affected by ephemeris errors than short baselines). The broadcast ephemeris message is a forward-prediction of expected satellite positions, and typically has an accuracy of 5m – 20m. Various agencies produce precise ephemeris messages based on post-mission data from wide tracking networks, and typical orbit accuracies are 5cm – 20cm (2 orders of magnitude better than the broadcast ephemeris). Some advanced baseline processing software allows satellite positions to be included as parameters in the adjustment, thus allowing for orbit-modeling (this is usually applied only to scientific-level projects with very long baselines). GPS projects with baseline lengths <10km are typically processed using the broadcast ephemeris. Projects with baseline lengths >10km can benefit from post-computed precise ephemerides. Projects in Canada using precise ephemerides should obtain them from the Geodetic Survey Division of Natural Resources Canada to ensure the highest level of consistency.

Satellite Health

Each satellite broadcasts a message indicating its present health (i.e., operational status). This message is set “healthy” only if all functions are operating correctly, and it is in a stable and predictable orbit. GPS receivers should be set to monitor the health message, and use only signals from healthy satellites. Note that there can be delays between the time when a satellite failure occurs, and the time that this is detected by the control segment and the health message changed. There can also be delays within a GPS receiver in detecting and responding to changes in the health message. For these reasons it is possible for corrupt GPS data to be tracked and recorded even if the health message is being monitored.

The US Coast Guard Navigation Center (NAVCEN) is the official civilian source for GPS information. NAVCEN issues GPS satellite status reports and **N**otice **A**dvisories to **N**AVSTAR **U**sers (NANUs) which alert users of forecast satellite outages, as well as describe any unplanned satellite outages. NANU bulletins are issued often (sometimes more than once a day), and it is recommended that the NAVCEN email listserver be used to automatically receive these messages as they are issued. NANUs should be checked before using satellite prediction software, and any planned outages should be considered to see the local effect on coverage. NANUs should also be regularly checked during surveys to be aware of any unplanned satellite outages that may have occurred (and which may prompt special processing).

2.2.2. PROPAGATION ERRORS (IONOSPHERE AND TROPOSHERE)

GPS signal propagation is predictable in the vacuum of space, but as the signal travels through the earth’s atmosphere it is slowed and distorted and this can result in significant GPS errors. The earth’s atmosphere can be divided into two regions, each causing different signal distortions. The *troposphere* is the lower region from the earth’s surface up to 50km **-** 80km altitude, and this is the region which contains water vapour (and where we experience weather). The *ionosphere* is the region above the troposphere to an altitude of approximately 1000 km. This region has a variable distribution of charged particles, influenced by geomagnetic activity and solar events. This region is where the “Northern Lights” are seen when the ionosphere is active following a solar flare.

Ionosphere

GPS signals passing through the ionosphere are delayed as they collide with charged particles. The effect is variable based on the distribution, density, and charge of the particles, with the delay amount being related to the signal frequency. This allows the ionospheric delay for each GPS signal path to be directly computed by dual-frequency receivers tracking both the L1 and L2 signals. This delay is unique for each GPS signal path, and it fluctuates over time. Single-frequency GPS receivers cannot directly measure the ionospheric delay, and must instead rely on general broadcast parameters that can produce an estimate of the delay.

The interaction of the sun's radiation and the earth's magnetic field results in 3 *geomagnetic activity zones* in bands centered on the earth's magnetic pole. These zones are shown in Figure 2 below. The level of ionospheric activity is generally highest and most unstable in the *Auroral Zone*, followed in intensity by the *Polar Cap*. The *Sub-auroral Zone* generally experiences lower levels of ionospheric activity.

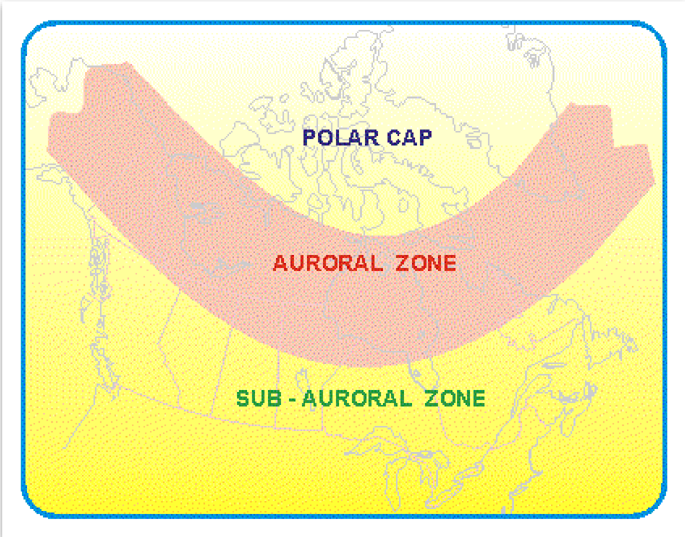


Figure 2 - Geomagnetic Activity Zones

The overall ionospheric activity level is related to a repeating 11 year solar cycle. The most recent solar activity peak was experienced in ~2001. Even though the solar peak has passed, and activity levels are generally declining until later in the decade, there are occasional solar events that cause significant problems for GPS users. An international panel of experts led by NOAA and sponsored by NASA has released a prediction for the next solar cycle – May 2009 (NASA). Solar Cycle 24 will peak, they say, in May 2013 with a below-average number of sunspots (Figure 3).

These forecasts should be consulted when planning precise GPS observations and the archives can be accessed to review the actual conditions at various geomagnetic observatories. The Geological Survey of Canada provides this forecasting service. An example of a long-term forecast is shown below. For more information, please refer to Natural Resources Canada Web site: **http://www.spaceweather.gc.ca** or NASA @Science **http://science.nasa.gov**

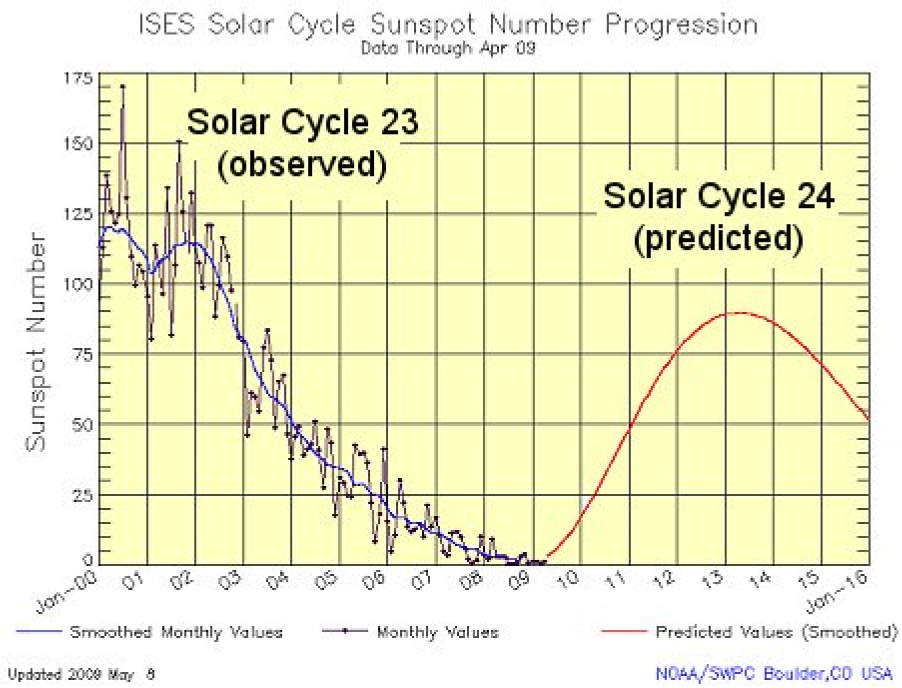


Figure 3 - Sunspot Numbers and Solar Cycle Chart

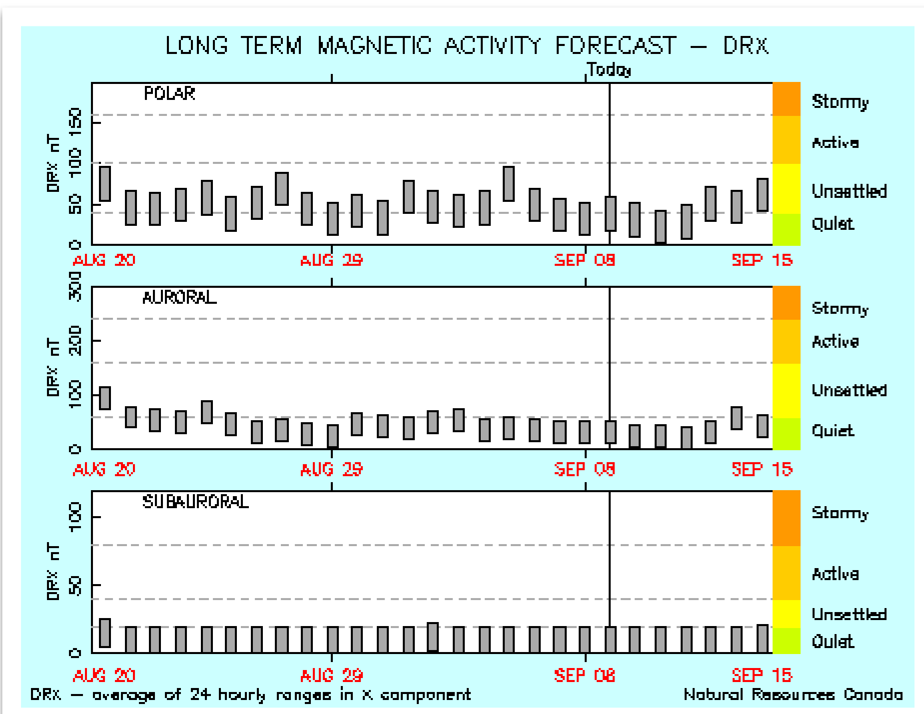


Figure 4 - Long-term Geomagnetic Activity Forecast for September 2009

The DRX values plotted are a forecast daily index representing the variability in the magnetic field intensity (units are nanoTeslas). This can be a useful indicator of the expected ionospheric stability. Note that the forecast plots have different scales for each of the 3 zones. For example, a DRX of 50nT is considered “quiet” in the Auroral Zone, “unsettled” in the Polar Cap, and “active” in the Sub-auroral Zone. Long-term forecasts are useful for general project planning. The short-term local forecasts should be consulted as the planned observation dates get closer in order to refine the schedule (and avoid solar storm events).

When the ionosphere is stable, the delays can be considered constant for GPS receivers within ~10km of each other (note that this distance is only a guideline, and it will vary +/- based on conditions). The optimum GPS baseline in this case is usually based on a single-frequency solution, with no ionospheric corrections applied. This is because applying ionospheric corrections from dual-frequency measurements add noise to the solution. If the ionosphere is unstable, or the GPS receivers are separated by larger distances, it *cannot* be assumed that the ionospheric delays are the same at both receivers. In this case the optimum GPS baseline solution is usually based on measurements that have been ionospherically corrected epoch-by-epoch, for each receiver (from dual-frequency observations). In this case the trade-off of increased observation noise is accepted to avoid the biases that could be induced by real differences in ionospheric delays experienced at the different receivers. This trade-off judgement is made by the data processor based on an understanding of the conditions and their impact, and supported by processing experience. Often this will involve an iterative approach before the optimum results are obtained.

Troposphere

GPS signals are also affected as they pass through the troposphere. Unlike the ionosphere, the tropospheric effects are not frequency-dependent, and therefore cannot be directly measured. Instead, empirical models have been built-up over many years of study to describe the tropospheric effects as a function of surface meteorological values and the elevation angles of the signal paths. Various tropospheric models exist, usually given the name of the scientist leading the study (e.g. Hopfield, Black, Saastomoinen, etc). It has been found that the surface meteorological values (wet and dry temperatures and pressure) must be very accurately measured at each receiver in order to produce accurate corrections. An alternative approach used by some processing software is based on a selected tropospheric model using an assumed “standard” atmosphere, with meteorological scale parameters being solved during the baseline adjustment processing. This approach removes the requirement for meteorological values to be observed at each GPS receiver, yet still produces accurate baselines in most cases. Processing experience may show that a particular tropospheric model works well in some conditions, and not as well in other conditions.

It is suggested that the general weather conditions be recorded during GPS data observations. Particular events to note are significant changes during observations (e.g. changing from clear conditions to intense localized thunderstorms). Sharp, fast moving weather systems passing through the observation area may affect the accuracy of tropospheric modeling, and therefore also the baseline accuracy.

The amount of the GPS signal path transiting the atmosphere is variable depending on the elevation angle of the satellite. The signal path from a satellite overhead (near the observer’s zenith) travels less than ½ of the distance through the atmosphere as compared to the grazing signal path of a satellite near the observer’s horizon (this is why the received signal strengths are weaker for low-elevation satellites). The atmospheric signal distortions become erratic and hard to model for grazing signal paths, and the result can be degraded observation accuracy. To minimize this problem, a cut-off elevation angle is usually set between 10 and 20 degrees above the horizon during processing. GPS receivers can be configured with a low cut-off angle (e.g. 10 degrees), and this can be revised later during data processing. Note that the cut-off elevation angle decision is trade-off balancing observation accuracy versus the solution geometry.

2.2.3. ANTENNA CONSIDERATIONS

The antenna is a physical sensor that detects GPS signals, and it is the measurement point for the observations. There are a number of antenna design types available, each with different characteristics related to the signal gain pattern, measurement point variability and stability, frequency(s), ruggedness, physical size, etc. Most control surveys are done with antenna sensors based on a ceramic microstrip patch that creates electrical current when contacted by GPS signals. Some antennas include a circular ground plane to limit reflected GPS signals from reaching the sensor. This can be further enhanced by adding a choke ring to destructively cancel reflected signals from below. Both ground planes and choke rings add to the size and weight of the antenna, and are usually used only for static applications.

All GPS antenna designs suffer from a characteristic that the signal measurement point does not correspond to a fixed physical point of the antenna. The Antenna Phase Center (APC) describes the electrical measurement point, and this moves both horizontally and vertically depending on the location of the signal source. This is obviously a critical consideration for precise GPS surveys (an analogy can be made with a prism pole "wobbling" during a conventional survey). One way to reduce the impact of APC movement is to use identical antenna types, and align them all in the same direction. This approach will result in the APC movements "cancelling-out" when the observations are differenced during processing. However, this approach only works when *all* antennas used on a project are the same type. If antenna types are mixed during a survey, and the APC movements are ignored, baseline errors on the order of 0.1m may be experienced.

This APC movement problem can be minimized by calibrating each antenna type to create a model describing the APC behaviour. This is done by making controlled measurements for each antenna type relative to a standard. The resulting antenna APC model is made up of 2 components:

1. APC Offset (the vertical distance of the phase center above a reference point on the antenna)
2. APC Variations (a table of phase differences (mm) at elevation angles from 10 to 90 degrees above the horizon)

Dual-frequency antennas have separate APC Offsets and APC Variation tables for each frequency. The APC Offsets and APC Variations can be applied during data processing to account for measurement differences caused by the different antenna APC movements. This antenna APC modeling process applies measurement corrections to allow different antenna types to be used together on the same project without inducing major errors, however, it should be recognized that this is not a perfect process. The best baseline precision is normally obtained when using identical antenna types aligned in the same direction.

The lead agency for GPS antenna calibrations is the US National Geodetic Survey (NGS). Other agencies and some equipment manufacturers also produce calibrated antenna APC models. Note that the calibration procedures and parameters are not identical, and therefore it is important to *not* mix these different antenna APC models during processing. The antenna APC models applied must be from the same source (e.g. all antenna APC models from NGS, or all antenna APC models from a specific equipment manufacturer).

Figure 5 below shows a GPS antenna diagram including the antenna height, physical reference point, phase center offset, etc. This diagram shows a GPS antenna installed on a pillar (with the vertical reference point being the top of pillar).

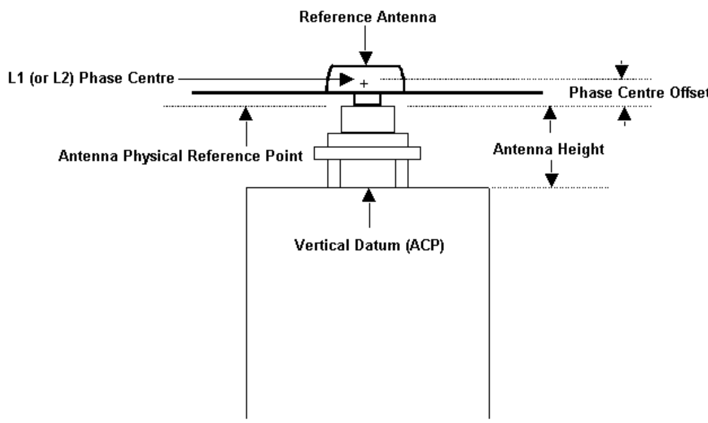


Figure 5 - GPS Antenna Diagram

2.2.4. GPS RECEIVER CONSIDERATIONS

There are many considerations when selecting a geodetic GPS system. This Section lists only those receiver considerations that can have an impact on accuracy.

- Single/Dual Frequency – On short baselines (<10km) there may be no difference in accuracy of the L1 solutions, however, dual-frequency receivers can resolve the integers more quickly (resulting in better productivity). Longer baselines are more accurate when ionospheric corrections can be directly computed from dual-frequency observations.
- Number of Channels – It is desirable to track all available satellites above the elevation mask to maximize the number of observations. Receivers with 10 or more parallel channels can effectively be considered as full view. Most receivers on the market are capable of tracking 12 or more channels.
- Measurement Quality – Receivers should be checked to ensure that the raw measurements (pseudorange & carrier-phase) are accurate and quiet. A GPS calibration is a good way to check the accuracy of the entire GPS system under controlled conditions. Some receivers use advanced signal processing techniques to produce high quality measurements that are less susceptible to reflected signals. This performance difference may not show on a GPS calibration basenet (because the basenet pillars have generally clear tracking), but it may have an accuracy impact under more difficult tracking conditions. An alternate testing scenario could be designed to measure this performance (e.g. series of stations setout conventionally online along a curb with trees / buildings / parked vehicles nearby).

2.2.5. TRACKING ENVIRONMENT

The environment around the GPS antenna is important, and can affect measurement accuracy. It is important to understand that GPS measurements are based on tracking of an extremely weak electromagnetic signal, which can be affected by:

- obstructions blocking all signals from a satellite (e.g. building, terrain, heavy tree canopy)
- partial obstructions weakening and distorting signals (e.g. light tree canopy)

- reflective surfaces creating multipathed signals (e.g. nearby vehicles, building surfaces, metal signs)
- radio transmitters interfering / distorting satellite signals (e.g. microwave communication antennas)
- nearby structures "coupling" or "imaging" with the GPS antenna to distort its reception pattern (e.g. vehicles, metal fences, towers, etc)

Obstructions that completely block signals affect the number and distribution of satellite measurements that will be available. This impacts the satellite geometry, and therefore also the baseline accuracy. If a site has a single obstruction, the station should be located to the South if possible to minimize satellite blocking. The obstruction impact can often be minimized by careful observation scheduling based on obstruction diagrams for each station. Note that some heavily obstructed stations may not be suitable for GPS occupation.

Stations that have partial obstructions should also be described on the obstruction diagrams, and observations planned based on the assumption that satellite measurements through the partial obstruction will not be useable. Observations sets that suffer from interrupted tracking (cycle slips) may not be useful. The data processor should carefully inspect satellite residuals and then decide if the measurements are acceptable to use. This choice may be aided by the recorded satellite signal strength values.

Multipath (reflected signals) remains a significant error source for GPS. This impact can be minimized by careful site selection to avoid nearby reflective surfaces. Some GPS antenna types are optimized to limit reflected signals from below the antenna. The local area surrounding the antenna (e.g. 15m) should be kept free of parked vehicles during observations. The data processor should carefully inspect satellite residuals and watch for short-term anomalies that may indicate multipathed signals. Re-processing with different control parameters can often eliminate the affected observations. Note that the short observation spans (5-15 minutes) of fast static occupations can make identification and removal of multipath more difficult than classic static GPS occupations with 30 minutes or more of data. This same comment applies (even more strongly) to kinematic and RTK surveys with occupation times <1 minute.

Radio transmitters in the observation area should be identified during project reconnaissance. GPS stations should be sited away from transmitters wherever possible, and avoid locations in-line with directional antennas (e.g. microwave communication dish antennas, directional radar, etc). Tracking problems can occur even though the transmission frequency is not the same as the frequency(s) of GPS. This can be due to harmonic frequencies and/or near field effects which can affect all receivers when operated within a few wavelengths of the transmitting antenna. Even low-powered handheld voice radios transmitting close to a GPS antenna can interrupt tracking and induce unwanted cycle slips.

GPS stations should not be located adjacent to metal chain-link fences, towers, or other structures that can electrically "couple" with the GPS antenna. Another term for this is antenna "imaging". The result is a distortion of the apparent location of the antenna phase center.

An important objective for precise observations is to allow the antenna to passively receive GPS signals in an environment that is as quiet and free of distortion as possible.

2.2.6. BASELINE PROCESSING

Processing GPS carrier-phase data to give reliable and precise baselines requires appropriate software, and also a data processor with the background and experience to properly apply the software. This is another example of when validation surveys can be useful. This Section highlights some of the accuracy considerations for data processing. More specific information is provided in Section 5 of this document.

Baseline processing software should include:

- satellite prediction utilities for mission planning & observation scheduling
- processing time windows (to specify start / stop times and ensure independent sessions)
- antenna APC modeling (APC Offsets & Variations…when mixing antenna types)
- external precise ephemeris support (for long baselines)
- "seeding" of accurate initial coordinates
- rejection of individual satellite data (all or portions)
- variable elevation cutoff angle
- integer ambiguity controls
- cycle slip detection / correction controls
- dual-frequency solution options (ionospheric corrections)
- tropospheric correction models
- process quality controls (e.g. outlier rejection controls)
- individual satellite residual plots
- comprehensive baseline result reports (including full covariance information)
- loop closure reports
- network adjustment (or links to separate software)

Baseline processing is usually done iteratively, with a first pass with parameters set to initial values, and subsequent passes following with parameters refined based on an analysis of previous results. Often it takes more than 2 iterations to get the optimum results. The quality indicators must be detailed enough to analyze the impacts of each processing decision. These indicators should show the strength of the satellite geometry used to generate the baseline solution.

Integer Ambiguity Resolution

Control surveys typically demand high precision, and this requires that the cycle ambiguities be correctly resolved to integers. Integer ambiguity resolution has evolved into a mostly automated step within baseline processing software, but this does not mean it is always correctly done. Incorrect integer ambiguities can produce baselines that are grossly in error (many dm), and yet the solution quality indicators may not always flag this as a problem. It is relatively easy to determine the correct integer ambiguities when the baseline separation is short, the ionosphere is quiet, and there is a long data span available. It may not be so easy when these factors are different. A strong signature of correct integer ambiguity resolution comes from the data "fit" as the satellite geometry changes over time (e.g. >30 minute span of a classic static survey). This signature is not as strong when considering the short time spans of rapid static data sets (5-15 minutes). Instead, these short data sets rely on the artificial *wide lane* solution that is formed from dual-frequency measurements in order to quickly resolve the integer ambiguities. This has proved to be generally reliable, but only when both the L1 and L2 signals are tracked without interruption, and the ionosphere is quiet. The processing software should provide statistical indicators describing the quality of the integer ambiguity resolution process, and the data processor should have experience interpreting this.

Integer ambiguity resolution may not be successful on longer baselines (over a few tens of km), as errors that grow with separation distance spill into the search for integers. These errors include ephemeris and atmospheric propagation, and therefore their quality affects the integer search. If the ephemeris message is accurate, and the ionosphere / troposphere are stable, it is possible to correctly resolve integers even on long baselines. Conversely, a poor quality ephemeris message and/or unstable atmospheric conditions can make finding the correct integer ambiguities difficult on even relatively short baselines. If the integer ambiguities cannot be *confidently* resolved, the best results may be a solution with the integers left "floating" (i.e. not fixed to integers). In this case the trade-off is accepting the known lower precision of a float solution, rather than the chance of being fooled by incorrect integer ambiguities which could induce gross errors. Most control surveys demand the precision of fixed-integer ambiguities for the internal network, and therefore a float solution would not be acceptable, and observations would have to be repeated.

A useful tool for baseline processing quality control is the loop closure utility. This allows a suspect baseline to be checked with other baselines that have been previously accepted. Loop closures should always include at least one baseline from an independent session. With a highly-redundant network, it is possible to form loops closures via different routes, and this can help isolate problem baselines.

Cycle Slips
Once the ambiguities have been resolved and fixed to integers, any tracking interruptions that cause a disruption of the continuous phase counts must be detected by the processing software. The detection process is simple if the tracking interruption is brief and sharp (e.g. someone stuck their head over the GPS antenna and blocked a satellite for a few seconds). The detection process is not so simple if the interruption was slow and gradual (e.g. a satellite signal path moving slowly into sparse trees, lost tracking for some minutes, and then gradually became clear and tracked again). Once a cycle slip has been detected, two options are available. The first option is to repair the slip by estimating the number of cycles that were lost during the interruption, and simply adding this to the phase counts that followed the slip. This option is appropriate for cycle slips that are brief and sharp. The second option is to treat the data before and after the slip as separate data sets, each with their own integer ambiguities. This second option is usually appropriate for longer tracking interruptions. The baseline processing software should allow controls for the way that cycle slips are handled. It is important to closely check the individual satellite residual plots surrounding any periods with cycle slips.

2.2.7. GPS VERTICAL ACCURACY CONSIDERATIONS

This Section describes special accuracy considerations when applying GPS to vertical surveys. Note that most GPS control surveys are done to establish only horizontal coordinates and the station elevations are established separately using conventional spirit-levelling techniques. There are exceptions to this, for example establishing remote stations that are far from existing vertical benchmarks.

Ellipsoidal Heights
GPS baselines are 3-dimensional vectors which can be expressed as differences in ellipsoidal latitude, longitude and height. These baseline coordinate differences are referenced to the same datum as the satellite coordinates in the ephemeris message. If the broadcast ephemeris is used, this datum is WGS84. If a precise ephemeris is used, the datum may be an international reference (for scientific projects), or it may be a national datum such as NAD83. Regardless of which datum the baseline coordinate differences are referenced to, an important concept to understand is that GPS heights and height differences are purely mathematical in that they are referenced to an ellipsoid. The notation used for ellipsoidal height is “h”. Unfortunately, ellipsoidal heights are not directly useful for most surveying and mapping applications. Note also that the height component of GPS solutions is generally less accurate than the horizontal components due to satellite geometry (VDOP generally > HDOP), unmodelled atmospheric effects, antenna APC movement, etc. A general rule of thumb is the height accuracy is 1.5 times horizontal accuracy.

Orthometric Elevations
The usual vertical elevation reference for surveying and mapping is Mean Sea Level (MSL), also called *orthometric* elevations. The notation used for orthometric elevation is “H”. These elevations are referenced to the geoid, and are thus tied to the gravity field of the earth (and this satisfies the truth that

water flows from a point with higher elevation to a point with lower elevation). Orthometric elevations are naturally suited to conventional survey equipment (e.g. levels, theodolites) as they use the gravity vector as a reference. In Canada, the network of levelled benchmarks connected to long-term tide gauges defines the CGVD28 vertical datum.

Geoidal Undulations

The separation between the geoid and the ellipsoid is called the *geoidal undulation*, and this is given the notation “N”. The geoidal undulation is the link between GPS-based ellipsoidal heights, and orthometric elevations (see Figure 6). The accuracy of GPS-derived orthometric elevations depends therefore on both the accuracy of the ellipsoidal heights, as well as the accuracy of the geoidal undulations.

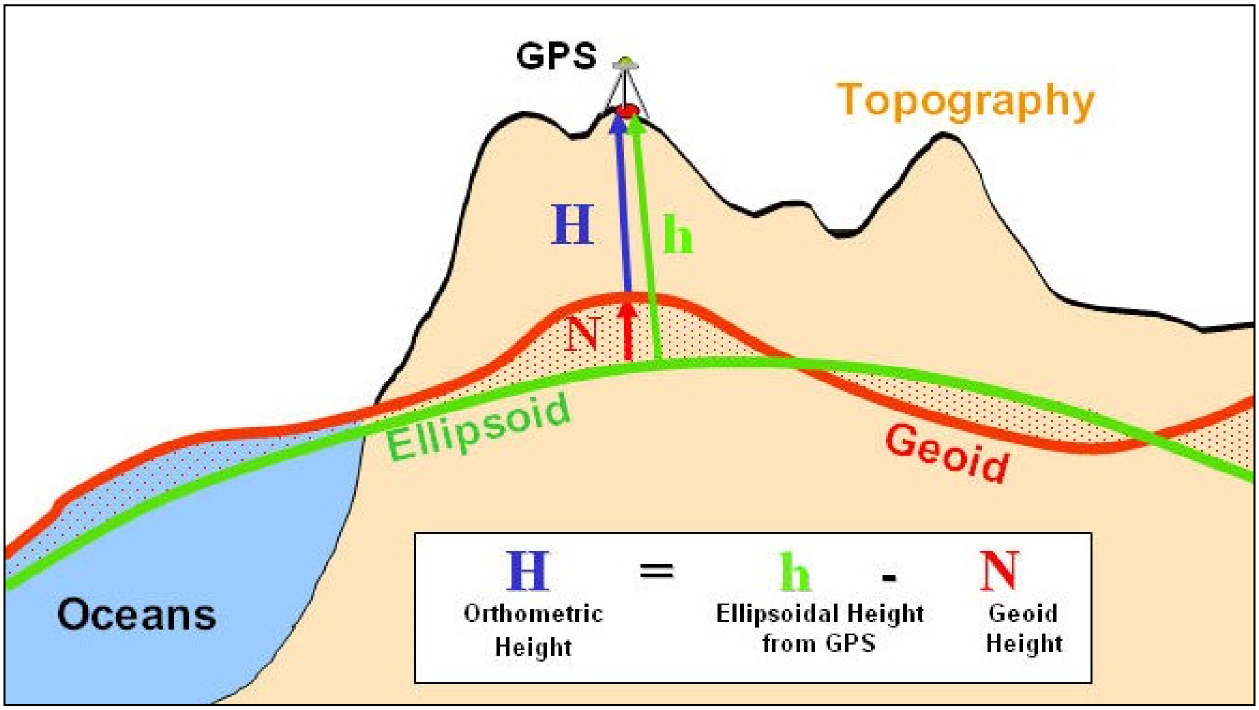


Figure 6 - Ellipsoidal Heights, Orthometric Elevations, and Geoidal Undulations

The geoidal undulation varies at different locations because of the irregular nature of the geoid, and it cannot be defined with a simple mathematical formulae. Instead, geoid models are built-up from gravimetric observations, and this is presented as a gridded array of locations each with a geoidal undulation value. Software is provided to allow the user to estimate the geoidal undulation at a specific location based on the surrounding grid values. There are many different geoid models available, with some intended for global use, others defined on a national level, and some specific to a very localized area. The information used to define geoid models changes over time as measurements are expanded and refined, and this result in occasional geoid model updates to reflect the improved accuracy. Geoid models are given an identifying name which usually includes an indication of the year the model was produced (e.g. geoid models OSU86, GSD95, CGG2000, etc). Note that the latest model year does not always indicate the most accurate geoid model for a specific project area (e.g. a global model produced in the current year may not be as accurate as a local model produced 3 years ago based on dense local observations surrounding the specific project area).

In BC, the most current province-wide geoid model is CGG2000. This model has been produced by the Geodetic Survey Division (GSD) of Natural Resources Canada, and is available free of charge. CGG2000 is classified as a scientific geoid model as it is determined solely from gravimetric data. In order to refine scientific models to better fit the imperfect vertical datum of Canada (CGVD28), height transformation models have been created which incorporate selected vertical control information from benchmarks across the country. These height transformation models use the scientific geoid model as a starting point, and then correct them to better fit the existing vertical datum. As more comparison information becomes available (i.e. GPS observations at known orthometric benchmarks), the height transformation model accuracy will continue to improve. The current height transformation model from GSD is called HT2_0. The CGG2000 geoid model and the HT2_0 height transformation model can be accessed via the GSD supplied software called GPS H2.1.

The absolute *Network Accuracy* of CGG2000 geoidal undulations range from a few centimetres, to a few decimetres depending on the amount of gravimetric information, and the shape of the geoid in the area. Flat areas such as the prairies are easier to model accurately than mountainous areas are. The absolute *Network Accuracy* of the HT2_0 height transformation model is estimated as being +/-5cm for most of southern Canada, but this may increase to several decimetres in remote areas where there are few accurate CGVD28 elevations to derive reliable transformations.

Note that geoid models can also be applied differentially, in which case the *relative* accuracy across the project area is of interest. This could be expressed as the *Local Accuracy* of the geoid model, and this is expected to range from sub-cm to a few cm for the CGG2000 model (depending on the size of the project area, variability of the geoid, density of gravimetric data, etc).

Computing Orthometric Elevations from GPS

There are a number of approaches to derive orthometric elevations from GPS, depending on the project objectives, and the available vertical control near the area. Care must be taken to ensure that any initial reference elevations used during processing are consistent with the chosen approach.

The simplest approach is to compute just a single geoidal undulation for the project, and apply this to all ellipsoidal heights to derive coarse orthometric elevations. This approach ignores any differences in the geoidal undulations across the project (which could be decimetres or more), and therefore the resulting orthometric elevations will likely have poor *Local Accuracy.*

A second approach is to apply a geoid model (or height transformation model) to every GPS station individually. This will improve the *Local Accuracy* of the derived orthometric elevations, but there may still be a significant bias of all the elevations (i.e. poor *Network Accuracy*).

If an accurate benchmark is available near the project site, and this can be observed within the GPS network, then a 3rd approach can be used based on applying a geoid model differentially with a bias correction. This is done by computing an offset bias at the benchmark to bring the GPS-derived orthometric elevation into alignment with the published value for this benchmark. This bias correction is then applied to the other GPS stations after the individual geoidal undulations have been applied. This approach has orthometric elevations with good *Local Accuracy* based on the geoid model, and has improved *Network Accuracy* as a result of the bias correction.

If there are 3 or more benchmarks surrounding the project area, it is possible to compute a project-specific geoid model directly by comparing the ellipsoidal heights with the benchmark orthometric elevations. The benchmarks must be well distributed around the project in order for this approach to be valid. The local geoid can be represented as a sloping plane surface if 3 benchmarks are available (more benchmarks will give redundancy or a check). Higher-order polynomial surfaces can be solved if enough benchmarks are available. Note that this approach has the advantage of directly computing the geoidal undulations at a specific site, but care must be taken to ensure that the results are valid.

3. GPS CONTROL SURVEY DESIGN

The Sections below describe the design objectives for a GPS survey control project, as well as guidelines for the preparation of the proposed project for submission to ESS for approval.

This document has been written to satisfy ESS requirements, but it can also be applied to any contracting agencies that require survey control referenced to the provincial GSR, and consistent with ESS standards.

3.1. DESIGN OBJECTIVES

The objective of GPS control projects conducted for the province is to physically and mathematically maintain the existing Geo-Spatial Reference (GSR). The physical component involves the location, installation and maintenance of new or replacement control monuments within the existing GSR. The mathematical component involves the survey observation network design and methodology that will ensure the desired *Network Accuracies* and *Local Accuracies* have been met.

There are different types and accuracy levels possible for GPS control surveys. Many of the design principles and procedures used for high accuracy GPS control surveys also apply to lower accuracy control projects. Section 6 of this document describes four types of GPS control surveys: Municipal horizontal control; High Precision Networks (HPN); GPS height transfers; and Geo-Referencing using the BC Active Control System (BC ACS). The accuracy objectives of each of these surveys may be different, but the basic design principles are similar.

3.1.1. PHYSICAL MONUMENTS

The physical objectives for monuments in a GPS control survey are to:

1. Ensure user accessibility by establishing new control monuments on public land or reserves (e.g. road allowances) wherever possible. Before starting the project field reconnaissance, a *title search* of all properties in the survey area should be done. This will facilitate contact with owners for either monument placement, or access across private property.
2. Ensure a suitable tracking environment for precise GPS observations (see Section 2.2.5). This includes avoiding locations with significant obstructions >15° above the horizon. Sites with nearby reflector surfaces should be avoided to limit multipath potential. Monuments should not be located adjacent to metal fences, towers, or other structures that could cause antenna imaging problems. Sites near transmitting antennas, especially on-line with directional microwave paths, should be avoided.
3. Ensure horizontal and vertical monument stability and survivability.
4. Ensure appropriate spacing between control monuments. Municipal survey areas are typically designed with framework monument spacing of between 800m and 2000m. The network objective may include intervisibility requirements between some of the monuments.

3.1.2. SURVEY OBSERVATION NETWORK DESIGN

The design of a GPS control survey observation network is a critically important step in achieving the project objectives. These objectives typically include a definition of the desired Network *Accuracy* and Local *Accuracy*. These accuracy terms are reviewed in the paragraph below for clarity.

This Section focuses on horizontal control networks as it is usual for the vertical network integration to be handled separately using differential spirit levelling techniques. Measuring elevation (z) using a GPS is acceptable where it is impractical to use a spirit level (e.g. measuring a rooftop GPS tracking station, and surveying in rural areas).

The concepts of *dependent* and *independent* baselines (also called *trivial* and *non-trivial*) must be understood before designing a network. These concepts can be illustrated by an example: Consider 3 receivers simultaneously measuring and recording raw GPS data. A baseline can be formed between receivers #1 and #2 by differencing their observations. Similarly, a baseline can be formed between receivers #1 and #3 by differencing their observations. At this stage, all the recorded GPS observations from this session have been used to form independent baselines. If the baseline between receivers #2 and #3 is then computed, this is being formed from observations that have already been used, and therefore it is called a *dependent* (or *trivial*) baseline. It is incorrect to assume that this is a new baseline that contributes to the network. The network design should be based on only the independent baselines from each session. Note that in the example described, it is valid to create independent baselines between any 2 receiver-pairs (e.g. a valid independent set can be 1-2, 1-3 or it could be 1-2, 2-3 or it could be 1-3, 2-3). This is a choice that is made based on the desired network configuration. If more receivers are used simultaneously in a session, the number of possible receiver-pair combinations grows quickly; however, the number of independent baselines will always be the number of receiver minus 1. If 4 receivers are used, there are 6 possible baselines, but only 3 are independent. If 5 receivers are used, there are 10 possible baselines, but only 4 are independent.

In order to meet the GPS control project objectives, a number of horizontal network design principles should be followed. The network design principles shown below are generic, and apply to most GPS control surveys (specific guidelines are included in Section 6 of this document).

1. The existing control stations selected to be included in the survey must have *Network Accuracies* equal-to or better-than the desired *Network Accuracy* of the project. Additionally, the selection should result in the existing control stations being distributed roughly equidistant around the new stations, and/or well distributed throughout the new stations.
2. Every new or existing station must be independently occupied at least twice. Independent occupations help minimize random and systematic set-up errors, and aids proper blunder detection (e.g. antenna centering, antenna HI measurement, and station miss-identifications).
3. Every new or existing station must be connected to at least two other stations, with baselines measured in at least two different observing sessions. Adjacent stations should be directly connected (see further comments below).
4. At least two network-wide baselines, oriented roughly perpendicular to each other, should be included to improve the determination of network scale and orientation.
5. Direct baseline measurements should be made between existing control stations as a confirmation check. This can confirm monument stability, as well as help to resolve any weaknesses in the existing control.
6. The baselines in each observing session should be approximately the same length (this will not always be possible).
7. A minimum of three GPS receivers should be used for GPS control surveys. Improved efficiency as well as increased station re-occupation and baseline repeatability can be gained by using four or more GPS receivers simultaneously.

One of the most important principles relates to the direct connections between stations in the network. There must be enough direct connections to ensure redundancy and strength in the network adjustment. The number of baseline connections to each station should be kept reasonably balanced to have a homogeneously connected structure throughout the network. The exception to this condition arises with the use of the *monitor station* integration method (also called the *fiducial station* method…see Section 4.1.1), in which case the monitor stations will have more connections than other stations in the network. With this method, all monitor stations should have a homogeneously connected structure, and they should have strong connections to the existing control framework (monitor stations can be located directly on existing control stations if they are suitable).

The following criteria should be used to determine when a direct connection between two stations is required:

1. Adjacent stations should be directly connected whenever possible, unless the monitor station approach is used. If adjacent stations are intervisible they should be directly connected regardless of the design approach used.
2. Two stations should be directly connected when the separation distance is <25% of the length of the shortest path through directly connected intervening stations. This is a good practice to prevent weak network geometry that would result in 2 stations being connected only by a long set of connections through other stations.

When it is considered impractical to satisfy the above criteria for a specific GPS project, the contractor is encouraged to contact ESS for additional advice.

3.2. GPS CONTROL SURVEY PREPARATION

3.2.1. RECONNAISSANCE

In carrying out the reconnaissance for a project, the contractor should refer to information in Section 3.1.1. Additional factors to be considered in selecting control monument locations may include:

- Marker stability
- Current and future access to the location
- Safety (e.g. vehicle traffic, cliffs, unstable slopes, visibility, etc)
- Long term marker usability / survival (e.g. tree growth, future development, etc)
- Presence of underground utilities
- Conventional survey sight lines (intervisibility)
- Accessible by a vehicle (if possible)

3.2.2. LANDOWNER CONTACT

Survey monuments should be placed on public lands whenever possible. There may be occasions when monuments must be placed on private property, or access across private property is required. The contractor must establish contact with the owner/occupant to explain the project and the need to access the property. If this is approached with tact and courtesy, consent is usually granted. Should the owner/occupant deny consent, then alternate monument locations must be considered.

3.2.3. UTILITY CHECKS

In order to avoid property damage, injury or possible loss of life, all proposed locations for new monuments must be checked for possible conflict with underground utilities. This process involves coordinating with the utility owners to visit each site, and if necessary making changes to the proposed monument location to avoid conflicts with underground utilities. This is to be done prior to submitting a proposed survey to ESS for approval.

3.2.4. SITE PREPARATION

The proposed monument location must allow a GPS antenna (or conventional instrument) to be safely and securely centered with a survey tripod. The proposed monument locations shall be uniquely and clearly marked in the field in a manner that will survive until the permanent survey monuments are installed.

Simple station descriptions should be made to help others find the locations. An approximate UTM position should be noted on the station descriptions (e.g. from single-point GPS). The type of survey marker suitable for the site conditions is to be indicated.

A station obstruction diagram can be done at this time, or it can be done later when the permanent survey monument is installed.

3.2.5. EXISTING MONUMENT CONFIRMATION

Any existing monuments that are to be included in the network should be checked to confirm stability and suitability. A *Monument Condition Report* (*See Appendix B*) is to be prepared and submitted with the report. A station obstruction diagram can be done at this time to support observation scheduling.

3.2.6. PROPOSED SURVEY SUBMISSIONS

The proposed control survey design information is to be presented in a report to ESS for approval. This report is to address all issues described here in Section 3, and any other issues that may have an impact on the survey. The report must indicate the GPS System proposed to be used, and a current validation for this full system is to be attached (see Section 7 for more information on GPS validation).

A plan drawing at a suitable scale shall be prepared to show existing and proposed monuments, as well as the proposed survey observation network.

3.2.7. ESS REVIEW AND APPROVALS

All survey control projects conducted for ESS must be reviewed and approved prior to commencing field operations. The submitted control survey design report and plan will be reviewed, and any comments or changes will be discussed with the contractor. A formal approval letter will be issued by ESS indicating authorization to install the new monuments. Following installation, monument location descriptions are to be submitted by the contractor. A letter authorizing data acquisition (collection of survey observations according to these specifications) will subsequently be sent to the contractor by ESS. On some projects ESS may issue a single approval to proceed with both the monument installation and the observations.

4. DATA ACQUISITION

This Section contains guidelines for data acquisition planning, equipment, and field procedures used during typical GPS control surveys. These guidelines provide general information for GPS control surveys, more specific guidelines for various types of control surveys are provided in Section 6 of this document.

4.1. PREPARATION

Typical steps done in the office prior to field data acquisition include:

- obtain a current satellite almanac and check PDOP figures
- check for any planned satellite outages
- review the planned baseline network (approved by ESS) and gather all support information
- confirm the receiver deployment scheme (e.g. leapfrog traversing, monitor station, modified, etc)
- identify any special baseline needs (e.g. longer cross-network ties, or control ties may be dual-frequency)
- plan detailed observation sessions for all desired independent baselines (obstruction diagrams needed)
- include repeat baselines

4.1.1. RECEIVER DEPLOYMENT SCHEMES

There are a number of receiver deployment schemes that can be applied to GPS control surveys. Each scheme has advantages and disadvantages in precision and logistics. Two of the more common methods are called *leapfrog traversing* and *monitor station*.

The leapfrog method is based on a traversing approach with the back receivers being moved forward (jumping over) the other receivers which remain at the same stations for consecutive sessions. The stationary receivers must be re-set in order to be considered an independent occupation of these stations. This scheme typically results in each station being independently occupied only the required number of times (a minimum of two times for most control projects). The monitor station scheme (sometimes called the *master* or *fiducial station* scheme) is based on a small number of stations within the project that are frequently occupied during the survey. These monitor stations, from which many baselines radiate, should be chosen based on their location within the network, and they should have good tracking conditions to allow strong connections to other stations. The monitor stations do not have to be at an existing control station, but there should be strong ties from these monitor stations to the existing control stations. Although the monitor station scheme may be logistically inferior, due to the need for simultaneous observations at 3 or more stations, it may produce superior results when there are 2 or more simultaneous monitor stations operating, along with 2 or more roving receivers. This scheme may be appropriate for small-scale projects in which the radiating baselines from the monitor stations are similar in length to the baselines between adjacent stations. When this process become “unbalanced” on larger-scale projects, unwanted distortions may influence the network and a different receiver deployment scheme should be used.

4.1.2. OBSERVATION SESSION PLANNING

Detailed observation planning based on the station obstruction diagrams enhances both the precision and efficiency of GPS control surveys. The only situation where there is of limited benefit is the case when *all* stations are completely clear of obstructions (in this case satellite planning software can be used simply to schedule the optimum coverage periods without consideration for obstructions affecting specific station-pairs). The normal case is to expect obstructions at some (or most) of the control survey stations. Satellite planning software is an important tool to schedule the best observation session for the desired independent baselines. The obstructions at both stations must be considered because the baseline is formed using only satellite observations that are simultaneously visible at both stations. After the obstructions have been combined to create a mask for a specific station-pair, the remaining satellites above the mask should be analysed for their balance and geometric strength. Some software planning utilities can create direct indicators of baseline strength for a specified observation session. If these are not available, the PDOP range can be used as an approximate indicator for the satellite constellation strength. Note that the integer ambiguities are more easily resolved under conditions of quickly changing geometry (e.g. a session with a PDOP starting at 8, and falling to 5 within 10 minutes indicates a quickly changing geometry). It is desirable to have satellites tracked in all 4 quadrants to give balanced coverage, however, this may not be possible to achieve for all baselines. An effective way to plan observation scheduling is to start with the most difficult baselines (i.e. worst combined obstructions from both stations) and then search all available coverage for the best observation session for this baseline. This process continues for the remaining desired baselines working from most difficult to easiest. Occasionally, the observation scheduling process shows that a specific baseline is not possible to achieve because of the combined obstructions being too limiting. In this case ESS is to be consulted to discuss alternate baselines connecting to these stations, or possibly moving the stations to reduce the problem obstructions.

The detailed observation session planning must include repeat baseline measurements to confirm reliability. These repeat baselines should be as independent as possible. The following list shows factors that contribute to the "degree" of independence (ranked from most important to least important…* indicates mandatory):

1. Independent antenna occupations at both stations *
2. Different satellite configurations (>1hr different session start times)
3. Different days
4. Different equipment (antenna / receiver / tribrach)
5. Different operators

Some projects specify what is considered acceptable for repeat baselines to be considered independent (e.g. HPN surveys require items 1-3, with >2hr difference in constellation times, and observations on different days).

4.2. EQUIPMENT CONSIDERATIONS

Refer to Sections 2.2.3 and 2.2.4 for background information on GPS antennas and receivers.

All equipment used on GPS control projects must be maintained in good condition. This includes the field support equipment necessary to achieve good accuracies (tripods / tribrachs / rangepoles / HI measurement tapes, compasses for antenna alignment, etc).

4.2.1. GPS ANTENNAS AND CENTERING EQUIPMENT

The following GPS antenna guidelines should be used for control surveys:

1. The antenna should have a ground plane and/or choke ring on projects being conducted in areas with significant potential for reflected signals from below. An example is an urban project with stations situated near significant reflector surfaces that cannot be avoided (e.g. parked vehicles, metal signs and structures).
2. The antenna must be stable and accurately centered over the monument during observations. This is usually done with either a tribrach set on a tripod, or with a rangepole with support bipod/tripod, to ensure antenna centering with 1mm accuracy. The tribrach plummet and level bubble must be checked / adjusted before each project begins, weekly for the duration of the project, and whenever there is an indication that the centering error may exceed 1mm. Note that tribrachs with rotating plummets and plate bubbles are more accurate and are easier to check than tribrachs with fixed plummets and circular bubbles. The rangepole circular bubble must be checked in a similar manner as described for tribrachs. The rangepole support bipod/tripod must be configured to ensure the antenna is stable and does not move with wind gusts.
3. The height of the antenna above the station marker is to be measured and recorded following the manufacturer's suggested procedures. The resolution of this antenna HI measurement is to be 1mm. This measurement is to be independently made and recorded at the beginning and end of each observation session (to avoid blunders, and detect settlement). A sketch should be included to show the height measurement process used (i.e. what physical point on the antenna was used for the HI measurement…this is be consistent with the antenna phase center offsets applied during baseline processing). *Accurate antenna HI measurements are required for all GPS control survey projects, even if other survey methods will be used to derive final station elevations*. If antennas are centered using a rangepole, only the fixed-height type of rangepole are acceptable for GPS control surveys. Attention must be paid to ensure that the tip of the rangepole reflects the correct measurement point on the monument (e.g. monuments set on sloping ground, or with deep center-punch marks may result in the wrong HI value being used).
4. If a baseline connects between antennas that are not of the same type, appropriate antenna APC modelling must be applied during baseline processing. The antenna types and the APC models must be the same as used during the GPS system validation. Whenever possible, antennas of the same type should be used, and they should all be aligned in the same direction (e.g. a compass can be used to align the reference marks on the antenna within a few degrees).
5. An independent occupation requires that the antenna be re-positioned (tribrach removed and re-set), and the antenna HI re-measured.
6. Activity near the antenna should be kept to a minimum to avoid disturbing the antenna or disrupting the tracking environment. In some cases this may mean re-directing pedestrian or vehicle traffic.

4.2.2. GPS RECEIVERS

GPS receivers used for control surveys must be geodetic quality (i.e. capable of accurate code and carrier phase measurements). Projects with baseline lengths <10km can be observed with single-frequency receivers. Longer baselines should be observed with dual-frequency receivers. It is valid for both single and dual-frequency receivers to be used on the same project. Any GPS system used for control surveys must have a current validation (see Section 7).

All procedures for the operation, system checks and maintenance of GPS receivers should be based on the manufacturer's instructions, and must be consistent with the procedures used during validation.

4.3. FIELD PROCEDURES

There are a number of different GPS field procedures that can be effective and appropriate in different circumstances. This Section does not prescribe a particular set of field procedures that must be applied; rather the advantages and disadvantages are presented for consideration.

Note: Field procedures selected for a project must be in general agreement with the procedures used during GPS system validation (see Section 7).

4.3.1. SAFETY

A safe work zone must be established first. Safety must be considered not only from the perspective of the field surveyor protecting himself and the equipment, but also from the perspective of others affected by the equipment safe area. If vehicle traffic needs to be diverted, this must be done with extreme care to make sure that the diversion is highly visible and with plenty of warning for drivers. Dedicated flag-person(s) may be required, and all personnel and equipment near traffic must be highly visible. Refer to safety guidelines from the Ministry of Transportation and Infrastructure, and WorkSafeBC.

GPS surveys are often done with operators working by themselves, sometimes in remote areas. Each operator should be equipped with a reliable form of communication, and periodic check-in times should be arranged throughout the day. Any sites that have dangerous access (e.g. steep or unstable slopes, fording a river, etc) should be planned when at least 2 people are available, and self-rescue equipment is carried.

4.3.2. FIELD LOGS

A detailed Field Log at each station shall be kept for each observation session. *Appendix A* shows a sample GPS Field Log sheet for static surveys. Typical information recorded in the Field Log includes:

1. Station identification (GCM number, tablet markings)
2. Session identification (including data file name)
3. Date (Julian Day and/or YY, MM, DD format)
4. Start and end times for session
5. Equipment model & serial numbers (receiver, antenna, tribrach)
6. Any non-standard equipment settings
7. Antenna heights before and after each session (measured and recorded to nearest 1 mm)
8. Diagram showing how antenna heights were measured
9. Operator name
10. General weather conditions during the session (note any fast-changing conditions)
11. Any problems encountered during the observation session

4.4. AFTER THE FIELD

The raw GPS data files are usually transferred to a computer each day following observations. This allows the data processor to quickly verify baseline quality by generating initial results, comparing repeat baselines, forming loop closures (see Section 5) and ensuring data security by backing up the observations. From this initial quality check, some re-observations may be scheduled.

5. DATA HANDLING PROCEDURES

The data handling procedures consists of processing, evaluation and reporting the results of the GPS survey. This also includes the ESS data submission requirements to allow integration within the provincial Geo-Spatial Reference (GSR).

The first processing task involves decoding the raw GPS observations and producing precise and reliable baselines. The next task is the evaluation and verification of the internal baseline consistency via a network adjustment of the baselines. This step is used to demonstrate that the survey met the project objectives for *Local Accuracy*. The final task is the integration of the complete survey into the provincial GSR, to allow the calculation of final published coordinate values for the new and/or existing control stations. This final task is the responsibility of ESS as it involves weighting and constraints issues of the existing control stations.

5.1. DATA PROCESSING AND EVALUATION

The specific details of data processing are different depending on the equipment and software used. Any GPS data processing methodology is acceptable as long as it produces verifiable quality results, it is consistent with the validation, and that all project objectives and submissions are met. The following Sections give some generic guidelines for GPS data processing.

5.1.1. DATA DECODING

Data decoding is the preparation of the raw recorded GPS data into the format required for baseline processing. This step typically includes transferring the raw data files from the GPS receivers each day. During this stage it is important to check the Field Logs to ensure that they are consistent with any information directly entered during field data collection. The type of information to be confirmed includes station identification, antenna type, antenna height (HI), and the measurement point for the HI. This is also a good time to review the Field Logs to see if any problems or anomalies were experienced during data collection. This information can be important during the baseline processing stage.

Some projects may include GPS data from more than one source (e.g. data from a permanent GPS tracking station such as the BC-ACS). This may require utility programs to convert this data into formats useable by the baseline processing software. This step should be done carefully, following a review of the utility program documentation. Particular attention should be paid to the measurement point for antenna HI referencing.

The following are general steps for data decoding of the raw GPS information:

1. Confirm that raw data has been transferred from all sources, and that the files are correctly identified (the daily session scheduling information can be used as a check-list)
2. Review the Field Logs to confirm / append any information that was entered in the field
3. Review the Field Logs for any noted problems or tracking anomalies
4. Note any errors during the transfer of raw data to the computer
5. Make a secure copy of the raw GPS data (e.g. external USB storage) before the raw files are deleted from the receivers.

5.1.2. BASELINE PROCESSING

GPS baseline processing software accuracy issues are outlined in Section 2.2.6 (e.g. integer ambiguity resolution, cycle slips, etc). This Section 5.1.2 expands the topic of baseline processing to address other issues that can affect the results.

Section 3.1.2 includes an explanation of dependent and independent baselines (also called trivial and non-trivial). It is assumed here that only the independent baselines are processed (exceptions are noted).

There are 2 general methodologies for generating baselines from static carrier-phase observations. The first methodology considers all available simultaneous observations from all receivers in a session, and generates a set of independent baselines with full covariance information from a single combined adjustment. This methodology is called *sessional,* and it is generally used only in advanced software. An alternate methodology is to form baselines and covariance information individually by considering only the observation data from each receiver-pair. This methodology is simply called *baseline* processing, and this is employed in most commercial software. In this case the data processor must select which baselines to process, and must ensure that they are independent in each session. This document is written assuming that the individual baseline processing methodology is applied (exceptions are noted).

Quality GPS baseline processing software has a number of control settings available to achieve optimum results from raw data of variable quality. Various commercial software hide some of these advanced controls, and encourage a more automated processing approach. This approach makes the software easier to sell and support, but it will not result in the optimum baseline results for every case. If the control settings are still available for the data processor to access and change as needed, then the automated process can be used during the initial pass, and subsequent processing can refine the settings to optimize the final results for each particular dataset. Another use of the automated process is to allow an initial quick verification of data quality on a daily basis immediately following downloading.

The following list shows typical steps during baseline processing. Each software package has different ways of handling these issues;

- Select the independent baselines to be processed (usually based on the original network design, but occasionally modified based on the specific data quality seen during baseline processing). In some cases, processing time windows may have to be set to ensure baseline independence.
- Consider if broadcast ephemerides are acceptable, or if precise ephemerides are needed for longer baselines (see Section 2.2.1).
- Confirm that consistent antenna APC modelling is being applied if using multiple antenna types.
- Confirm that the key processor control settings are at initial values for the first pass.
- Confirm that accurate 3D coordinates have been seeded (e.g. start baseline processing from an existing control station with accurate NAD83 latitude, longitude and ellipsoidal height).
- Process the independent baseline(s).
- Individually inspect each baseline processing report, and carefully analyse the quality indicators (e.g. observation RMS, variance factor, integer ambiguity resolution indicators, observation outlier counts, individual satellite residual plots, etc). See additional notes below.
- Re-configure the processor control settings based on the quality analysis of the initial pass, and re-process each individual baseline. Typical changes to enhance baseline quality include: time windowing, satellite rejection (complete or partial), outlier rejection criteria, integer ambiguity resolution controls, cycle slip detection / correction controls, ionosphere correction modes, elevation masks, etc.
- Analyse the revised baseline processing report, and continue to refine the control parameters and re-process iteratively until the optimum results are obtained for each baseline.

- When the optimum solution is achieved, the key control settings used, and the resulting quality indicators for each baseline are to be recorded in a summary table (this information is required in the final report).

The individual satellite residual plots are key quality indicators for a baseline solution. These plots show the fit of each satellite's observations throughout the session, and this information is useful in a number of ways. If satellite residuals show distinct trends over time, this may be an indication of incorrect integer ambiguities. The residuals can be inspected before and after a cycle-slip to determine if the repair was correct. The residual behaviour can be compared between satellites when considering rejecting a specific satellite (either completely or partially). It is also instructive to view satellite residual plots when comparing different solution types (e.g. fixed-integer, float, ionospherically corrected, etc).

Section 2.2.6 describes the accuracy impact of incorrect integer ambiguity resolution. Finding the correct integers can sometimes be tricky and the quality indicators can be deceptive, particularly with short data sets. It can be helpful to compute the *dependent* baselines as a check. Another processing issue is whether ionospheric corrections should be applied for a particular baseline solution. Loop closures and repeat baselines can help with these decisions.

In some cases, in may not be possible to accurately resolve the desired baselines because of a lack of common data (this will not usually happen if the station obstruction plots are accurate, and session planning has been correctly done). It may be possible to form different baselines from this session, but all baselines must still be independent (and the original baseline may have to be re-observed).

It is important to emphasise that baseline data quality is affected by the choices that the data processor makes. Clearly, the background and experience of the data processor is critical, and that is why this person is a key part of the GPS system that is validated (see Section 7). The data processor must have a comprehensive understanding of precise GPS concepts, and must be able to apply those concepts during data processing.

5.1.3. BASELINE RELIABILITY CONFIRMATION

The reliability and precision of GPS baselines can be verified with repeat measurements and loop closures. Loop closures are only valid if they include baselines from at least 2 independent sessions. These internal reliability checks should be done routinely as a way of detecting blunders, and to indicate if the project objectives are being met as the data is processed. If repeat baselines and/or loop closure checks indicate unexpected discrepancies, additional baselines should be measured to isolate or replace the problem baselines.

If there is an opportunity to form repeat comparisons using a *dependent* baseline (that otherwise would not have been processed), this should be done. However, in most cases only the *independent* baselines are considered during the network adjustment.

Short baselines (few km) typically show repeatability of <0.010m horizontal and <0.015m vertical (assuming reasonable ionospheric conditions, good satellite geometry, correct integer ambiguity resolution, few cycle slips, etc). Longer baselines will typically show worse agreement. It is suggested that the project's *Local Accuracy* values could be used as guideline for determining if a specific repeat baseline comparison was acceptable (this would be applicable only for the baselines connecting adjacent stations). For example, if a project's *Local Accuracy* was defined as 0.010m horizontal, and 0.020m vertical (ellipsoidal), it would be expected that the repeat baselines connecting adjacent stations would show agreements better than 0.010m horizontal, and 0.020m vertical. If the agreements are worse, the suspect baseline may be possible to isolate using loop closures, or additional baseline observations may have to be done.

A similar approach can be applied to testing the loop closure comparisons, but the tolerance value will likely have to be larger than the *Local Accuracy* values to reflect the error contributions from multiple baselines.

Note that the final decision to reject a specific baseline solution may not happen until the network adjustment phase (unless it was an obvious blunder).

The final report will require a summary table of all repeat baseline comparisons. Loop closure checks are not usually required to be submitted in the report.

5.2. REPORT AND SUBMISSIONS

The production survey report is the main source of information for judging the satisfactory completion of the project. Sufficient information must be provided to allow ESS to confirm that the objectives of the GPS survey were met. The summary of report items and submissions identified in Table 1 represents the minimum required for a GPS project. A checklist is provided in *Appendix D*, however, additional information may be required, and it is the responsibility of the contractor to identify and provide all relevant information. Note that all information required for re-processing of the GPS data (should it be necessary) must be provided.

5.2.1. SURVEY REPORT

Each production survey report must include a short description of the survey location, the aim of the survey and the number of new and existing monuments in the network.

There must be a clear description of the survey procedures used during the field surveys. Copies of the Field Logs are to be provided, plus the following information (and any other relevant field information):

1. Description of the field GPS equipment used on the project (receiver models, antenna types, etc).
2. Description of the field GPS configuration settings (elevation mask, data logging intervals, etc).
3. Description of antenna centering and HI measurement methods (including check/adjustment details).
4. Details of any conventional surveys done to enhance or supplement the GPS survey.
5. Names of all field and supervisory staff on this project.
6. List of actual observation sessions (showing date, times, stations/ receivers/staff, anomalies, etc).
7. List any logistical difficulties encountered (access, unexpected tracking problems, etc).

There must be a clear description of the procedures employed in the office, and these procedures must be consistent with those used during the validation survey.

If conventional survey observations are included in a project, the field and office procedures are to be fully described in the report. Conventional surveys are described in the parallel document: ***Specifications & Guidelines for Control Surveys using Conventional Survey Technology (July, 2009).*** Please click on the following link to access the document: **http://archive.ilmb.gov.bc.ca/crgb/gsr/specs**

If the contractor is required to produce initial coordinates and elevations based on a fully-constrained adjustment, a description of the approach and all results must be included in the report.

5.2.2. SUBMISSIONS

Table 1 below shows details of the project information to be submitted to ESS. This is the minimum amount of information normally required. Additional information may be required in order to successfully evaluate and integrate the GPS survey within the provincial Geo-Spatial Reference (GSR). Note the following when preparing project information for submission:

1. Raw GPS observational data in the manufacturer's native format must be submitted on CD (or storage accepted by ESS), and this must be properly labelled and described. This raw GPS data may also be required in RINEX (Receiver INdependent EXchange) format if requested by ESS. All raw GPS data used to generate the accepted baselines is to be provided to ESS.
2. All processed baseline information is to be submitted to ESS. This must be descriptively labelled and grouped according to observation sessions.
3. All control stations must be identified by the GCM number (not the tablet markings or any other ID scheme). If GCM numbers have not been assigned for new stations, contact ESS. The GCM numbers are to be used for all input and output data files, plans, etc.
4. The data required by ESS for the final constrained network adjustment is to be in either GHOST or GEOLAB format (see *Appendix C*). Baseline observations must be provided in position-difference format. Contact ESS if further information is required.
5. The MASCOT project number should be used in the header record of submitted files (MASCOT is explained below).

MASCOT (MAnagement of Survey Control Operations and Tasks), is the system used by the province for collecting, processing and managing geodetic survey data. (Web site: **http://apps.gov.bc.ca/apps/mascotw**) MASCOT incorporates several sub-systems capable of entering, editing, reducing, adjusting and analysing GPS and conventional survey data prior to integrating it within the existing GSR. ESS will supply a MASCOT project number that is to be used to identify the survey project within the MASCOT database. This number should be prominently displayed on all submissions (CD, project report, plans, etc).

Station descriptions are required in MASCOT format for any new control stations established. These descriptions are to be provided in both graphical (hardcopy) and ASCII text (digital) format (see *Appendix C*).

Any conventional survey observations are to be submitted according to the details described in the parallel document: Specifications & Guidelines for Control Surveys using Conventional Survey Technology (July, 2009).

DATA ITEM	FORMAT	
	Digital	Hard Copy
Daily diary (optional)	Yes	No
Baseline Information (optional)	Yes	No
MASCOT Station Descriptions (new stations)	Yes	No
Marker condition reports (existing stations – optional)	Yes	No
Network adjustment INPUT		
Minimally-constrained (un-scaled)	Yes	No
Fully-constrained (if requested)	Yes	No
note: all baselines to be grouped and identified by session ID, and the format must be either GHOST or GEOLAB (position-difference)		
Network adjustment OUTPUT		
Minimally-constrained	Yes	No
Fully-constrained (if requested)	Yes	No
Network plan (showing all stations and accepted baselines)	Yes	No
Catalogue list of all submitted data files (explicit definitions of file content and usage)	Yes	No

Table 1 - Contractor Data Submissions for GPS Production Surveys

6. SPECIFIC APPLICATIONS

This Section describes specific types of GPS surveys for establishing or maintaining control within the provincial Geo-Spatial Reference (GSR). General guidelines for conducting GPS surveys have been discussed in Sections 3, 4 and 5. It is not the intent of this Section to duplicate these Sections, but rather to expand on the requirements for specific applications. GPS control surveys can be carried out to various levels of accuracy and reliability using a variety of techniques. The methodology used to meet the accuracy requirements is generally left to the individual contractor. However, certain procedures are required to be carried-out in order for accuracies to be verified by ESS. If the contractor intends to deviate from these guidelines, it is their responsibility to ensure that accuracies can be verified, and ESS must approve any deviations prior to the production survey.

6.1. GEO-REFERENCING & AZIMUTH DETERMINATION

GPS control projects can be geo-referenced and azimuths determined by tying to the BC Active Control System (BC ACS). The BC ACS is a network of 15 precisely located dual-frequency continuous tracking GPS receivers spread throughout the province (see Figure 1). There are different approaches to geo-referencing and azimuth determination that can be applied, based on the project objectives and the project location within BC. The project location determines which BC ACS station(s) are suitable for baseline ties. The project objectives will determine the specific survey methodology.

Geo-referencing typically applies only to projects away from urban areas (which usually have dense control and/or a local ACS^m available). The baseline ties to the BC ACS stations can be very long, in some cases several hundred kilometres. This requires careful consideration regarding the type of equipment to be used, the stability of the ionosphere, and observation planning (see Section 2.2).

6.1.1. ACCURACY STANDARD

An example accuracy objective for a geo-referencing project may be:

Network Accuracy: 0.2m
Local Accuracy: 0.02m (between stations on the project site)

The *Network Accuracy* is achieved by the baseline ties to the BC ACS. This determines the absolute accuracy of the established station coordinates with respect to the defining GSR. The *Local Accuracy* is achieved by the baseline ties between stations in the project area. The azimuth accuracy requirement for a specific project will influence the chosen *Local Accuracy*. Note that some projects may specify only the *Network Accuracy,* as there may be no requirement for an accurate azimuth determination (and therefore the *Local Accuracy* may not be specified).

6.1.2. EQUIPMENT

A minimum of 2 GPS field receivers are required for most geo-referencing projects.

- Dual-frequency geodetic receivers are recommended, especially when baseline lengths are greater than 100km.
- Single-frequency receivers may be acceptable for less demanding *Network Accuracies* and/or shorter baselines.

Note it is possible to mix both single and dual-frequency GPS receivers on a geo-referencing project. The long baselines from the BC ACS stations can be processed to the dual-frequency receiver, and the short on-site baseline(s) can be processed between the single and dual-frequency receiver-pair. This approach is valid as long as it was included in the validation.

6.1.3. FIELD PROCEDURES

- Static GPS methodology is **mandatory** for geo-referencing projects.
- The duration of the observation sessions is the responsibility of the contractor. Factors that must be considered include: baseline length, accuracy objectives, ionosphere activity, and the type of GPS equipment used (i.e. single or dual-frequency). Observation scheduling is important to ensure balanced GPS coverage (satellites in all quadrants) and strong geometry.
- Scenario 1 on the following page shows 2 stations in the project area tied to 2 BC ACS stations. This is the recommended scenario for most geo-referencing projects as it includes redundancy checks, as well as a comparison baseline between the 2 BC ACS stations.
- Scenario 2 on the following page shows 2 stations in the project area tied to only 1 BC ACS station. This scenario is acceptable when the project area is located relatively close to one BC ACS station (e.g. <50km), but it is a long way from any other BC ACS stations (e.g. >400km).
- In either scenario, baselines are required to be measured in at least two independent sessions. This requires that the antennas be re-centered between sessions (see Section 4.1.2).

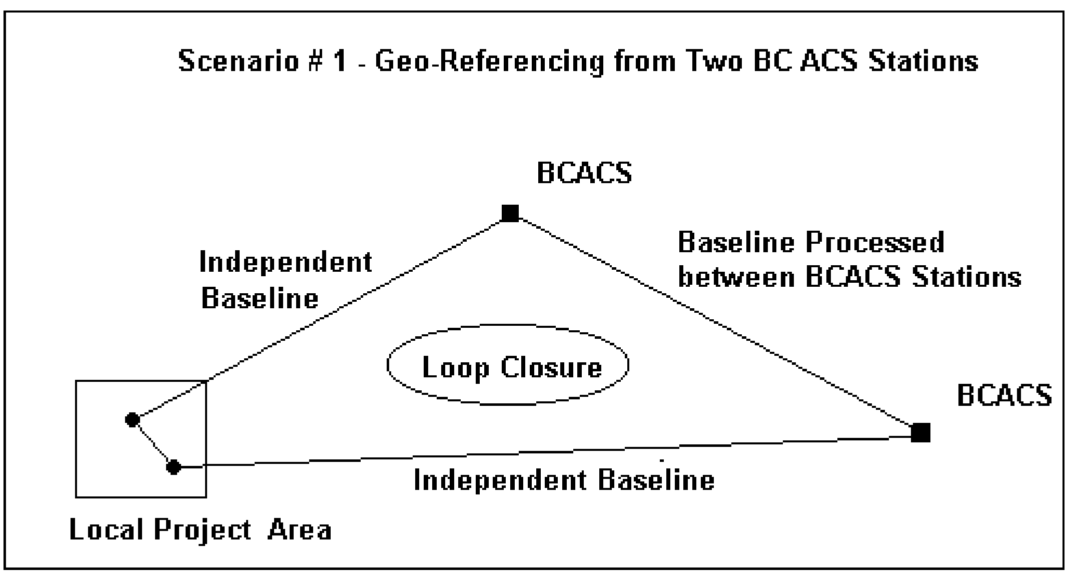


Figure 7 - Geo-referencing Observations Scenario #1

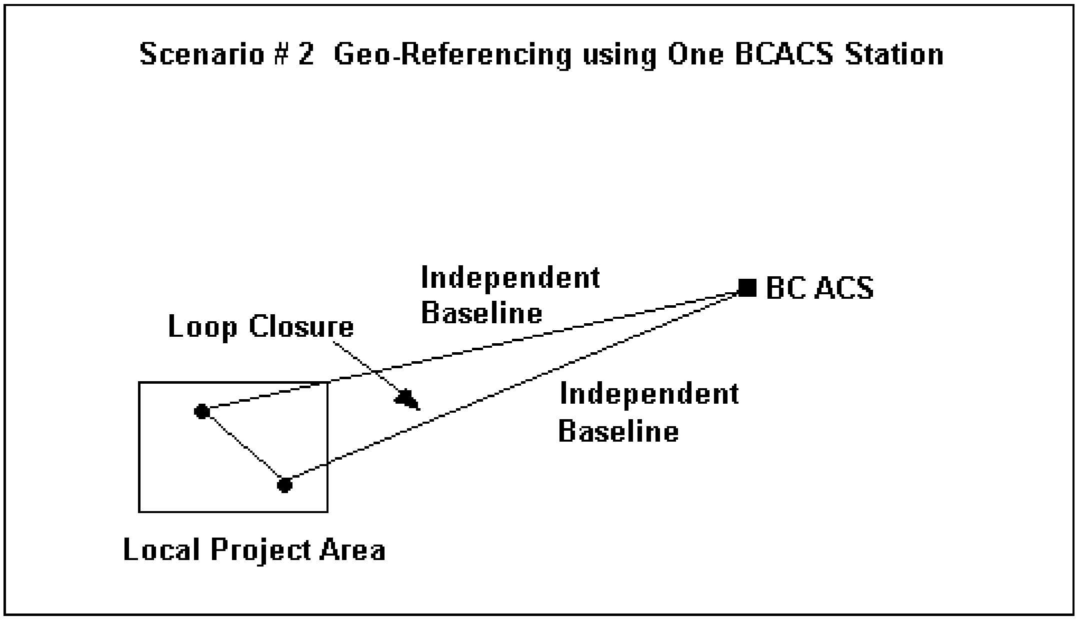


Figure 8 - Geo-referencing Observations Scenario #2

6.1.4. OFFICE PROCEDURES

- If multiple antenna types are used on the project, antenna APC modelling should be applied during baseline processing (see Section 2.2.3). Antenna details for BC ACS stations can be found on the ESS website.
- When two or more BC ACS stations are used to geo-reference a GPS project, the baseline(s) between the BC ACS stations should be processed and compared to the known values. This will give an indication of the ionospheric effect on the different baseline solution types.
- Precise ephemerides may improve accuracies, especially on very long baselines.
- It is recommended to process both the independent and dependent baselines in each session (note this is an exception to the general rule, and not all baselines will be used during the network adjustment).

6.1.5. RELIABILITY AND ACCURACY

- The baseline between the 2 stations in the project area will typically be measured at least twice in independent sessions. These repeat baseline measurements should be compared, and the coordinate discrepancies should be less than the specified *Local Accuracy*.
- Any repeat baselines from a project station to a BC ACS station should be compared, and the coordinate discrepancies should be less than the specified *Network Accuracy.*
- Loop closure checks should be done to confirm the internal baseline consistency. Each loop closure must include baselines from at least 2 independent sessions. Loop closures should include all stations and all processed baselines. In scenario 1 (ties to 2 BC ACS stations), the closure between the 2 BC ACS stations should be the theoretical baseline (computed from the published station coordinates).
- If the geo-referencing project also includes height transfers, the loop closures should include elevations discrepancies. Section 6.2 should be reviewed before using GPS for height transfers.

- The project objectives will define the way that the final results are computed. If the objective is to generate a precise local framework allowing an accurate azimuth determination, then the final network adjustment may include BC ACS ties to only 1 of the project stations. This will prevent errors in the long baselines from rotating and distorting the local framework. In this adjustment approach, one of the local stations will appear to be "hanging" (although it will be determined by at least 2 independent baselines). The formal determination of *Local Accuracy* and *Network Accuracy* from the adjustment output should be considered when choosing the adjustment approach. This adjustment approach may not be appropriate if the project objectives were different.
- The *Local Accuracy* for the project stations may be determined from the 95% relative confidence regions computed from a minimally-constrained adjustment. Be aware that the low redundancy, and unbalanced baseline lengths typical of geo-referencing projects may distort the adjustment statistics.
- The *Network Accuracy* for the project stations may be determined from the 95% station confidence regions computed from a constrained adjustment. The BC ACS stations can be considered an errorless connection to the GSR. Be aware that the low redundancy, and unbalanced baseline lengths typical of geo-referencing projects may distort the adjustment statistics.

6.2. GPS LEVELLING (HEIGHT TRANSFERS)

Most GPS projects are designed to produce only accurate horizontal coordinates, and the vertical elevations are determined separately by conventional survey methods. There are exceptions to this, including projects that are far from existing vertical benchmarks, or situations where conventional methods are not practical, and in these cases GPS height transfers (also called GPS levelling) may be appropriate.

There are special considerations necessary when using GPS to transfer heights. Section 2.2.7 describes these issues, including the differences between ellipsoidal heights and orthometric elevations, and this Section must be understood before undertaking GPS height transfers.

The fundamental relationship is described by the equation below:

H (orthometric elevation) **=** **h** (ellipsoidal height from GPS) **–** **N** (geoidal undulation from a model)

This Section assumes that a geoid model is applied to derive orthometric elevations. Some special projects may use GPS to directly model the geoid on a project site that has surrounding benchmarks available. This special application is not discussed in this Section.

6.2.1. ACCURACY STANDARD

The accuracy of GPS-derived orthometric elevation differences depends on two factors:

1. The accuracy of the GPS-derived height differences (ellipsoidal),
2. The accuracy of the geoidal undulation differences (from a model).

The first factor is easy to determine as it is derived from the network adjustment statistics in a similar manner as the horizontal accuracies. Most LS adjustment packages generate separate horizontal and vertical confidence regions. Be aware that most GPS networks have better horizontal accuracies than vertical accuracies.

The second contributing factor is not so easy to mathematically define. Section 2.2.7 describes the expected *Local Accuracy* of current geoid models when applied differentially, and also the expected *Network Accuracies* of the geoid models when applied in an absolute manner. These accuracies are estimates as supplied by the agency creating the model, and these are variable depending on the location, surrounding gravimetric data, shape and smoothness of the geoid, and the extent of the project area. A common methodology for GPS height transfers is to vertically reference the project to 1 or more benchmarks with know orthometric elevations. In this case, any bias in the undulation model can be removed at the benchmark(s), and the geoidal undulation accuracy is improved because it is being considered in a differential mode rather than an absolute mode.

An example accuracy objective for a GPS height transfer project may be:

Ellipsoidal height *Local Accuracy*:	0.02m	(between adjacent stations on the project site)
Orthometric elevation *Local Accuracy*:	0.05m	(between adjacent stations on the project site)

Both the ellipsoidal height and orthometric elevation *Local Accuracies* are shown in the above example to demonstrate their differences, however, many projects specify only the orthometric values.

The true vertical *Network Accuracy* is more difficult to define because of the nature of the vertical datum across Canada. Alternatively, a project may specify a vertical accuracy requirement relative to one or more defining benchmarks.

6.2.2. EQUIPMENT

- Dual-frequency geodetic GPS receivers are required for baselines >10 km,
- Best results are obtained when using identical antenna-types with all receivers (all antennas aligned). If the tracking environments include unavoidable reflector surfaces, antennas with ground planes or choke rings should be used to limit multipath effects,
- Use GNSS-capable receivers capable of tracking other satellites (e.g. Glonass, Galileo, etc.).

6.2.3. FIELD PROCEDURES

- Static GPS methodology is mandatory.
- GPS observation scheduling must be planned based on balanced coverage (satellites in all quadrants if possible), with geometry suitable for good vertical positioning (e.g. low VDOP), and with appropriate session durations.
- Antenna HI values must be carefully measured and recorded. It is recommended to measure the HI twice using different units (i.e. metres and feet/inches).
- Each station must be independently occupied at least twice.

6.2.4. OFFICE PROCEDURES

- If multiple antenna-types are used, antenna APC modelling must be applied during baseline processing.
- Orthometric elevations are derived as the last step following baseline processing, and network adjustment. In some cases, the best vertical results will be obtained by using the ellipsoidal heights from a minimally-constrained adjustment, whereas in other cases it may be appropriate to use

ellipsoidal heights from a constrained adjustment. The specifics of each project, including the availability and distribution of vertical benchmarks, will define which approach is appropriate.

- The newest and most local geoid model should be used to derive orthometric elevations from the ellipsoidal heights. The best results are usually obtained when the geoid model is applied differentially with a bias removal at a benchmark with known elevation. The contractor must decide if a scientific geoid model is to be used (e.g. CGG2000), or if a height-transformation model is more appropriate (e.g. HT 2_0). Contact ESS for project-specific advice.

6.2.5. RELIABILITY AND ACCURACY

- Vertical loop closures should be computed to indicate the internal consistency of the GPS ellipsoidal height differences. Each loop must include baselines from more than one session. All stations and all processed baselines should be included in loop closure checks.
- The computed 95% relative vertical confidence regions to adjacent stations are averaged to create the ellipsoidal *Local Accuracy* for each station.
- The 95% relative accuracy of the geoidal undulations is to be estimated from the published information (available from the agency that created the geoid model). Ideally, this undulation accuracy estimate should also reflect the experience gained with the model when applied on similar projects, in similar areas. If adjacent stations are close (e.g. <1km), and the geoid is smooth and well defined, this relative undulation accuracy estimate can be as good as 1-3cm. This estimate will increase as the station spacing increases, and in areas where the geoid changes rapidly. Contact ESS for further guidance.
- The orthometric *Local Accuracy* values are formed from the ellipsoidal and undulation accuracy values described above. This is formed using the error propagation formulae: square root of the sum of squares. As an example, if a station's ellipsoidal *Local Accuracy* is 0.015m, and the estimated relative undulation accuracy is 0.025m, the resulting orthometric *Local Accuracy* would be 0.029m:

$$0.029 = w\ (0.015)^2 + (0.025)^2$$

- The example *Local Accuracy* values shown above are within the ellipsoidal and orthometric accuracy specifications shown in the example in Section 6.2.1.

6.3. MUNICIPAL GEO-SPATIAL REFERENCE CONTROL SURVEYS

Municipal Geo-Spatial Reference (MGSR) control surveys include the establishment, densification or maintenance of monumented municipal control areas within the provincial Geo-Spatial Reference (GSR). Previously, these municipal control survey areas were identified as Integrated Survey Areas (ISA), and many were established conventionally dating from the 1960s. The accuracy standard for these ISA areas was generally 2nd order (note that survey "orders" are no longer used). Most of the existing MGSR areas have been upgraded with a framework of controlling GPS stations to integrate them within the provincial GSR, and to keep local network distortions to a minimum. Nowadays, GPS is mostly used to establish new MGSRs, as well as to replace and/or densify monuments within existing MGSRs. Some municipal projects benefit from the use of conventional horizontal survey measurements to augment the GPS observations. The station orthometric elevations are usually established by spirit-levelling. Conventional control surveys are described in the parallel document: **Specifications & Guidelines for Control Surveys using Conventional Survey Technology (July, 2009).** Click link to access the document: **http://archive.ilmb.gov.bc.ca/crgb/gsr/specs**

6.3.1. ACCURACY STANDARD

The *Local Accuracy* class specification for MGSR survey projects is:

Line Distance	Horizontal *Local Accuracy* class
< 2km	0.02m
2km - 3km	0.03m
3km - 4km	0.04m
> 4km	0.05m

GPS is not used to establish orthometric elevations for most MGSR projects. However, it is often used as a comparison and blunder-check for the conventional observations.

6.3.2. EQUIPMENT

- Single or dual-frequency GPS receivers are acceptable.
- Best results are obtained when using the same antenna-types with all field receivers.
- GNSS compatible receivers increase productivity and provide better DOP figures.
- Receivers should be equivalent or similar models to ensure tracking characteristics are constant.
- Firmware should be the latest version that is fully tested previously.

6.3.3. FIELD PROCEDURES

- All stations must be independently occupied at least twice.
- Below are recommended for each observation session:
    - 15 minutes duration for dual-frequency, or 25 minutes duration for single-frequency receivers
    - 5 or more satellites above 15° elevation angle
    - uninterrupted tracking for most satellites, for most of the session
    - PDOP < 4 for most of the session
- Projects establishing a new MGSR require direct GPS baseline ties between all adjacent stations.
- Monuments within an existing MGSR that was originally established by GPS must have strong network connections, but not all adjacent stations must have direct baseline ties. Adjacent stations do not have to be directly connected to the baseline route if route distance is not more than 3 legs. Also the route distance should not be more than 3 times the direct distance between these stations.
- Monuments within an existing MGSR that was established conventionally may experience GPS tracking difficulties at some existing stations. If these stations are not suitable for GPS observations, yet they are adjacent to the new project area, conventional survey ties should be included to ensure proper integration, and alternate stations should be tied with GPS baselines.

6.3.4. OFFICE PROCEDURES

- If multiple antenna-types are used, antenna APC modelling must be applied during baseline processing.
- Network adjustments that mix GPS and conventional survey observations must have realistic weights for each observation type. If the GPS-only adjustment shows an aposteriori variance factor that is significantly greater than 1, the baseline input covariances should be scaled before adding the conventional observations to the adjustment.

6.3.5. RELIABILITY AND ACCURACY

- Repeat baseline discrepancies (N, E) should not exceed the corresponding *Local Accuracy* value (this is 0.02m for baselines under 2km length, and 0.05m for baselines over 2km length).
- Loop closures should be computed to confirm baseline consistency. Each loop must include baselines from at least 2 independent sessions. All stations and all processed baselines should be included in loop closure checks.
- The minimally-constrained adjustment should show the GPS baseline residuals (N, E) being less than 2/3 of the corresponding *Local Accuracy* value (this is 0.013m for baselines under 2km length, and 0.033m for baselines over 2km length). Any conventional observation residuals should be within the equipment measurement expectations (check closely if any are flagged as outliers).
- An indication of the external accuracy can be seen by comparing coordinates from the minimally-constrained adjustment with the published values at all existing stations. The fully-constrained adjustment and analysis will be done by ESS.

6.4. HIGH PRECISION NETWORK CONTROL SURVEYS

The recent development of municipal Active Control Systems (ACS^m) has made precise GPS positioning possible in real-time as well as post-mission within the coverage areas. This development has forced the existing monumented system to be upgraded in order for it to be compatible with these higher precisions, and this has created a special category of GPS control surveys to accomplish this upgrade. These upgraded control monument networks are called High Precision Networks (HPN). An important component of HPN surveys is the accurate modelling of the geoid throughout the coverage area with a dense network of stations having both accurate GPS ellipsoidal heights and spirit-leveled orthometric elevations. This improved local geoid model can then be applied by GPS users within the ACS^m to derive better orthometric elevations.

An HPN GPS control survey is typically comprised of 4 separate phases (listed below). The field survey for these phases does not have to be conducted simultaneously, or in any particular order. The accuracy requirements are different for each phase, as is the procedures required to obtain and verify these accuracies.

a) Framework survey
- Ties to at least 4 BC ACS and/or Canadian Active Control Stations (CACS)
- Typical baseline lengths: 10km to 250km

b) F10km grid survey
- 10km grid spacing is required in rural areas to create a homogeneous reference system.

c) 2km grid survey
- Approximately 2km grid spacing is required in urban areas to provide a homogeneous reference system.

d) Precise spirit levelling
- Refer to: ***Specifications & Guidelines for Control Surveys using Conventional Survey Technology (July, 2009)*** **http://archive.ilmb.gov.bc.ca/crgb/gsr/specs**

6.4.1. ACCURACY STANDARD

The *Local Accuracy* specifications for the different phases of HPN surveys are listed below. Below are Standard Deviation numbers expected at 95% level in the network:

Phase	Horizontal	Vertical (ellipsoidal)
A) Framework survey	0.010m * [km]	0.015m * [km]
B) 10km grid survey	0.010m	0.015m
C) 2km grid survey	0.010m	0.015m

The *Network Accuracy* of an HPN survey is controlled by the quality and distribution of high-accuracy stations (such as CACS tracking stations) available in the region. This will vary between projects, and therefore it is not possible to specify a universal *Network Accuracy* in this document. However, it is known to achieve results mostly better than the posted specs above.

6.4.2. EQUIPMENT

- Dual-frequency GPS receivers are required.
- GNSS compatible receivers are recommended for better productivity and lower DOP figures.
- A minimum of four GPS receivers must be deployed simultaneously during observations (preferably all receivers to be the same make and model).
- GPS antennas with ground planes are required (choke-rings are recommended if available). All antenna used for the project observations are to be of the same type (exceptions are allowed when integrating GPS data from existing permanent tracking stations).

6.4.3. FIELD PROCEDURES

- Static GPS methodology is mandatory.
- If there are permanent GPS tracking stations within the project area, their data should be downloaded and integrated to form baseline connections to the HPN stations where appropriate.
- GPS antennas must be stable and accurately centered during all observations. The maximum allowable centering error is 1mm, and the maximum allowable HI error is 3mm. Level bubbles must be shaded for at least 3 minutes prior to checking or re-plumbing.
- Double occupancy is required at all stations, and at least 50% of the stations must be independently occupied three or more times.
- Baselines connecting adjacent stations must be observed at least twice on different days and at different times (>120 minutes difference in the GPS constellation timing).
- Observation sessions must be planned to include a minimum of 5 satellites that are available for 75% of each session.
- Observation sessions must be planned during periods when the Position Dilution of Precision (PDOP) is less than 4 for at least 75% of each session.
- Observation sessions must be planned during periods when the Vertical Dilution of Precision (VDOP) is less than 4 for at least 90% of each session.
- Phase A) Framework survey sessions must be at least 12hr duration.

- Phase B) 10km grid survey sessions must be at least 1hr duration.
- Phase C) 2km grid survey sessions must be at least 0.5hr duration.

6.4.4. OFFICE PROCEDURES

- Phase A) Framework survey: precise ephemerides are **required**.
- Phase B) 10km grid survey: precise ephemerides are **recommended**.
- Phase C) 2km grid survey: broadcast ephemerides are **acceptable**.
- If multiple antenna-types are used, antenna APC modelling must be applied during baseline processing.
- Baseline quality shall be verified by careful analysis of the statistical indicators (e.g. RMS, variance factors, individual satellite residual plots, etc). Any anomalous baselines need to be reprocessed for enhanced results.

6.4.5. RELIABILITY AND ACCURACY

- Repeat baseline discrepancies should not exceed the corresponding *Local Accuracy* values shown in Section 6.4.1 above. For example, repeat baselines in the Phase C) 2km grid survey should agree within 0.01m horizontal, and 0.015m vertical.

Minimally-constrained adjustments:

- Each Phase of the project is to be adjusted independently with minimally-constrained adjustments to confirm meeting the project objectives. ESS will complete the final constrained adjustments to integrate the project within the provincial GSR, and derive a local geoid model.
- The 95% relative confidence regions between adjacent stations are to be averaged to create the *Local Accuracy* values for each station, and for each Phase of the HPN project. This is to be done for both the horizontal and vertical components. These *Local Accuracy* values must meet the specifications shown in Section 6.4.1.

7. GPS SYSTEM VALIDATION

While a GPS system validation is required when a control survey is to be included in the provincial GSR, ESS does not require submissions from the validation process, unless specifically requested. This and subsequent sections are indented primarily as a guide, however, where a contractor seeks assistance from ESS in the validation process or where ESS specifically requests it, the provisions of this section (including subsections) are required.

A GPS system validation must be performed to verify that the complete system can achieve accuracies fitting for various types of GPS control surveys in BC. The validation survey is similar to a production GPS survey; except that it is carried out on a basenet or permanent pillars with high accuracy 3D coordinates. This allows ESS to confirm the internal and external consistency of the contractor's validation results. Here, the GPS system is defined by:

- GPS receivers (make, model, firmware version)
- GPS antennas (make, model, ground plane & configuration)
- Field support equipment (tripods, tribrachs, rangepoles, HI measurement & antenna alignment aids)
- Baseline processing software (version)
- Network adjustment software (version)
- Office staff (for planning, supervision, processing, adjustments, reporting)
- Field staff (for system set-up and data collection)

All of the above can be verified during a GPS validation survey, with the exception of the Field support equipment (the basenet pillars have forced-centering attachments for the antennas, and therefore tribrachs are not used). Field methodologies are described in Section 4.2.1 to ensure the antenna centering and HI measurement is accurate and reliable during production surveys.

The GPS system validation remains valid for a period of 1 year, as long as the system is not significantly changed. Examples of significant changes that would require a re-validation include (contact ESS for clarification if necessary):

- Change of receiver, or a firmware change that affects tracking or measurement accuracies
- Change of antenna type or configuration (e.g. adding a ground plane to an existing antenna)
- Change of baseline processing software, or a version change that impacts baseline results
- Change of network adjustment software, or a version change that impacts network results.

There are two GPS validation basenets available in BC: one is located in the lower mainland (Greater Vancouver GPS Validation Network), and the other is located near Vernon (Okanagan GPS Validation Network). Both validation basenets were established and operate on a co-operative basis with the Geodetic Survey Division (GSD) of Natural Resources Canada, the Province, and municipal agencies. Each basenet consists of stable concrete pillars with spacings varying from under 1km to over 65km. This allows almost any combination of baseline lengths to be replicated during a validation survey.

Contractors may wish to use a basenet to do an internal self-validation of their GPS system. ESS is available to help evaluate the validation data, if requested to do so, provided that the submissions are in the required format.It is important to emphasise that the validation survey must be completed in a similar manner as a full production survey. **The preceding Sections of this document should be read and understood *before* reading Section 7.**

7.1. THE VALIDATION PROCESS

The validation survey is to be designed and executed using the same system as that proposed to be used for future GPS production surveys. The validation planning should consider different types of equipment that may be used (either individually, or mixed), different baseline lengths to be included, different session durations (e.g. rapid static, classic static), and other scenarios that may arise on future production surveys. A well planned validation survey should be applicable to more than one type of GPS control project.

7.1.1. VALIDATION SURVEY DESIGN AND DATA ACQUISITION

The validation survey design and data acquisition is to replicate the production surveys as closely as possible (see Sections 3 and 4). This includes consideration for baseline length, observation session durations, receiver deployment schemes, dependent / independent baselines, reliability measures, etc. As an example, if a production survey is planned to be observed with session durations of 0.5hr, then the validation survey should include similar length baselines observed with 0.5hr duration sessions. If rapid-static observations are planned for production surveys, then these must be included in the validation survey.

It is advised that validation surveys include specific stations in order for ESS to complete the evaluation. Validation surveys using the Greater Vancouver GPS Validation Network should include GCM 336131 as part of the network for best results. Similarly, GCM 436444 may be included when using the Okanagan GPS Validation Network. These stations will be fixed during the network adjustment evaluations.

7.1.2. VALIDATION DATA HANDLING

The processing, evaluation, reporting and data submissions are similar to that described in Section 5 of this document, however, there are some specific differences for validation surveys concerning the Least Squares (LS) adjustments and data evaluation. These differences are described below.

It is important for the contractor to confirm the reliability of the validation survey through baseline satellite residual analysis, repeated baseline comparisons, and loop closures checks. This information is an indicator for both the contractor and ESS in determining the quality of the validation survey.

7.1.2.1. VALIDATION LEAST SQUARES ADJUSTMENT

The contractor shall perform a LS adjustment to derive 3D NAD83 coordinates for the validation basenet stations. The adjustment is to be an un-scaled minimally-constrained adjustment of the contractor's observed baselines. The full formal covariance matrix of the adjusted parameters is to be extracted and provided for evaluation. A complete list of required submissions for validation surveys is shown in the Table below.

The minimally-constrained validation adjustment should be performed with horizontal and vertical constraint equations using either GCM 336131 (Greater Vancouver Validation Network), or GCM 436444 (Okanagan Validation Network) for optimum results. The coordinate values to be used and the associated constraint equation information are provided by ESS. *Appendix C* (GEOLAB Format Input file) shows example constraint equations to be used for the 2D/1D parameters.

7.1.2.2. VALIDATION DATA EVALUATION

The evaluation of the internal and external validation survey accuracy includes the assessment of the strength of the observation network design, the influence of errors and unmodelled biases, and the compatibility of the derived solution with *known* values. The *known* values for both BC validation basenets are derived from the highest accuracy GPS techniques available (e.g. choke-ring antennas, extremely long observation sessions, advanced data processing, etc). As with a GPS production survey, the validation data evaluation is divided into two parts, the internal and external accuracies.

Internal Accuracy

The internal accuracy is evaluated using the covariance matrix from the minimally-constrained network adjustment, as well as analysis of the individual baseline residuals. All possible 95% relative confidence regions (1D vertical, 2D horizontal and 3D spatial) are derived from the network covariance matrix. The semi-major axis of these confidence regions must meet the project accuracy standard for specific types of GPS control surveys (see Section 6).

External Accuracy

The external accuracy of the submitted GPS coordinates is assessed by examining their compatibility with the known station coordinates, including an evaluation of any network-wide or local distortions. Discrepancies between the submitted GPS coordinates and the known values are analyzed using specific statistical tests and network strain analysis. It is noted that the reliability of this assessment increases with the number of comparison stations. Contractors must consider the trade-off between cost efficiency (few basenet stations) and reliability of the evaluation (more basenet stations). However, the number of stations included in the validation survey design should ultimately be dictated by the type and design of the GPS production surveys. Contact ESS for guidance on these considerations.

The external accuracy evaluations performed by ESS are shown below. These are presented in a technical format for those readers with an interest in these evaluations. It is not required for these evaluations to be done by the contractor.

External Accuracy - Compatibility

Assessment of the external accuracy is carried out via an evaluation of the contractor's solution for statistical compatibility with the known solution using the Chi-square test.

$$\Delta x^T (C_{\Delta x})^{-1} \Delta x \le \chi^2_{(u,1-\alpha)}$$

The Δx vector is composed of differences between corresponding coordinates at the known stations. The $C_{\Delta x}$ matrix is the sum of the two covariance matrices associated with the coordinates from the contractor's solution and the known control. χ is the abscissa of the Chi-squared distribution function for a significance level of α. u is the number of parameters being tested.

Various combinations of the coordinates may be tested together by defining Δx and $C_{\Delta x}$ in different ways. The tests performed during a validation assessment include:

1. Δx containing only the 3D coordinate differences (N, E, H) at a single station (u = 3)

2. Δx containing only the North coordinate differences (u = number of stations)

3. Δx containing only the East coordinate differences (u = number of stations)

4. Δx containing only the Height coordinate differences (u = number of stations)

5. Δx containing only the 2D horizontal (N, E) coordinate differences (u = 2 times the number of stations)

6. Δx containing all the 3D (N, E, H) coordinate differences (u = 3 times the number of stations)

The above Chi-square tests of coordinate-difference components of the total network (tests 1 to 5) are performed *out-of-context* from the other parameters; that is, they neglect the presence of the other parameters. These tests may also be performed *in the context* of the other complementary tests so that the simultaneous probability of these tests is equal to the desired confidence level (see Vanicek and Krakiwsky [1986]).

The *in-context* tests are performed in exactly the same manner as the *out-of-context* tests, except that the significance level α/m is used in place of α, where m is the total number of parameters divided by the number of parameters used in the test. For example, test 1 requires using α/s in place of α (s is the number of stations in the network), tests 2, 3 and 4 use α/3 and test 5 uses 2α/3. Test 6 uses all parameters, and thus the *out-of-context* and *in-context* tests are the same for this case.

External Accuracy - Network-wide Distortions
A Helmert transformation of the contractor's submitted station coordinates can be performed solving for up to seven parameters (3 rotations, 3 translations and scale) describing the "fit" to the known coordinates. This determines any systematic network-wide differences in scale, rotation, or translation between the contractor's solution and the known solution for the validation stations.

One purpose of this evaluation is to detect any unmodelled biases in the contractor's GPS data, which could result in network-wide distortions. Another purpose could be to identify the failure cause (if needed) of the statistical compatibility test described above.

External Accuracy - Local Distortions
Strain analysis can be performed to detect any local distortions between the contractor's solution and the known solution. Local distortions are quantified in the form of strain ellipses and differential rotations. This analysis may be performed using the techniques described by Craymer et al. [1987].

7.1.2.3. VALIDATION DATA SUBMISSIONS

The required input data can be either in GHOST or GEOLAB (V2 or V3) formats (see *Appendix C*). All submitted data must use the appropriate GCM numbers to identify the basenet stations for both digital files and hardcopy. Table 2 outlines the data submission requirements for GPS validation surveys.

GEOLAB V2 or V3 extracted output file containing the adjusted coordinates and covariance matrix information from the minimally-constrained adjustment must be in *position equation format*. Please note that this requirement is different from production surveys which require *position differences* and covariances.

DATA ITEM	FORMAT	
	Digital	**Hard Copy**
Daily diary (optional)	Yes	No
Field Logs (optional)	Yes	No
Baseline solutions (optional)	Yes	No
Network adjustment INPUT Minimally-constrained (un-scaled) - GHOST format (or GEOLAB V2 or V3 format) - Contractor adjustment note: all baselines to be grouped and identified by session ID	Yes	No
Network plan (showing all stations and baselines)	Yes	No
Network adjustment OUTPUT Minimally-constrained - adjusted coordinates - confidence regions - residual analysis - variance factor analysis	Yes	No
Validation data file (Appendix E or alternate format) - adjusted coordinates - covariance matrix of parameters - observation connections	Yes	No
Catalogue list of data files (explicit list of file content and usage)	Yes	No

Table 2 - Contractor Data Submissions for GPS Validation Surveys

APPENDIX A

GPS Field Log Sheet

Fill out a new log sheet for every rover file

Location of project: ____

Date and Start Time: ______________________________End Time: _______________

Project Name/ ID#:____

Operator's Name(s): ____

Rover Filename: ____

Data Dictionary Name: ____

GPS unit: ______________________________ Height of Instrument (HI): _____________

Reference Material Used: ____

GCM # (Unique marker ID) : ____

FEATURE:	**NOTES:**
	Include documentation sources, Land owner addresses, any threats to resources, etc.

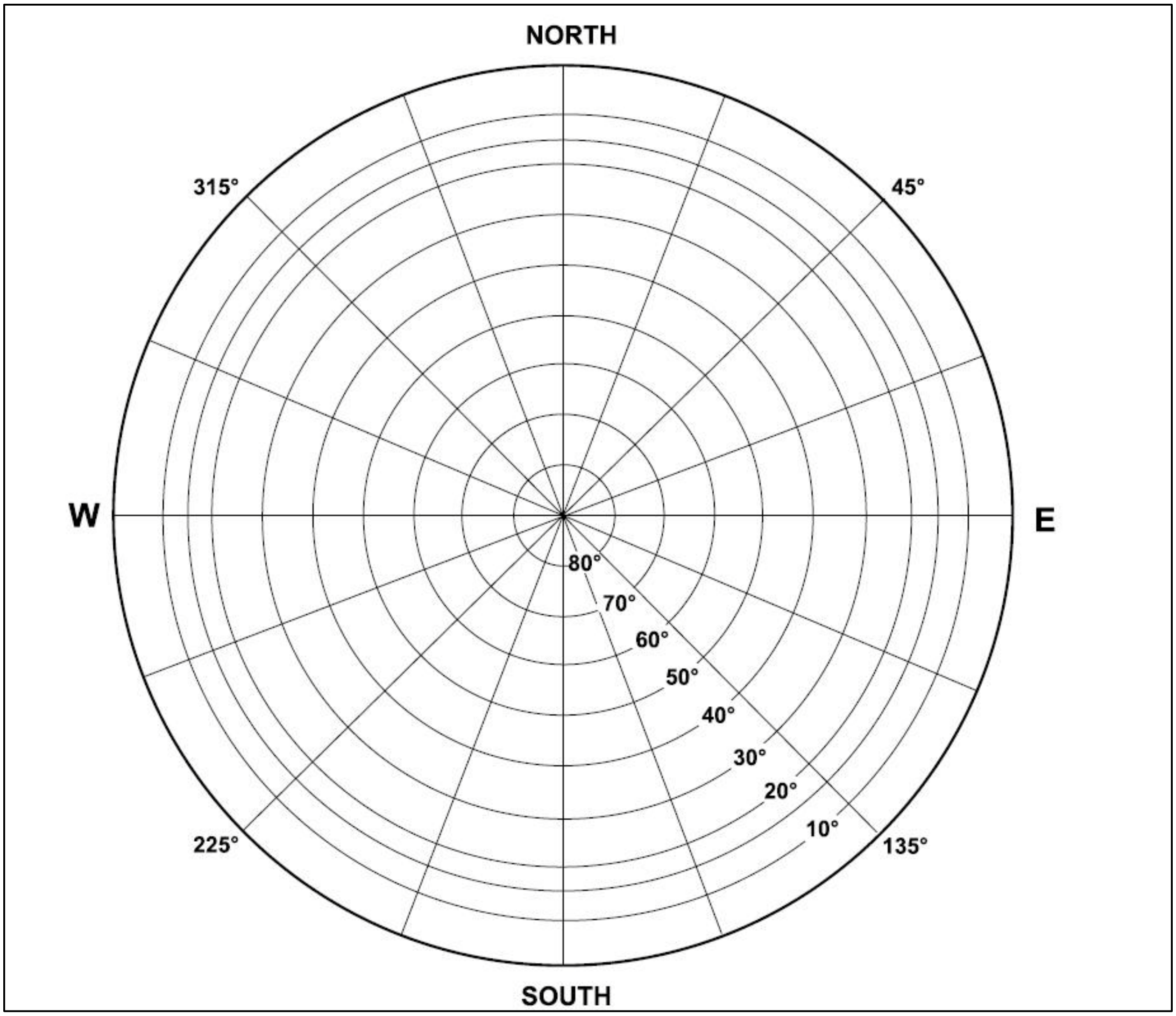
Post-Processing:

Base station Location: ____

Export Coordinate System: L/L-dms L/L-dm UTM StatePlane Other: ______________________

Export Horizontal Datum: NAD83 NAD27 WGS84 Other:______________________________

GPS Observation Sheet



GPS Station Horizon mark up diagram

Station ID:		**Observer:**		**Date:**
Magnetic Azimuth or Bearing	Vertical Angle from Horizon	Blockage Feature Description	Approximate Distance (m)	Other useful comments

APPENDIX B

Survey Monument Condition Report

To access report on-line go to: **http://apps.gov.bc.ca/pub/mascotw/**

Submitted by:	Phone No:
Organization:	Fax No:
Date (YY/MM/DD):	Email:

GCM #: (Unique Marker ID)
Bolt/marker number: (Number found on bolt)
Condition: <u>Select One:</u> Good Condition , Cap Missing , Pipe Bent , Other Disturbances , Not Found , Destroyed
Approximate Location: (Civic Address - preferred or Lat/Long, UTM, etc)
Remarks: What makes you suspect that the condition of this monument has changed?

GCM #: (Unique Marker ID)
Bolt/marker number: (Number found on bolt)
Condition: <u>Select One:</u> Good Condition , Cap Missing , Pipe Bent , Other Disturbances , Not Found , Destroyed
Approximate Location: (Civic Address - preferred or Lat/Long, UTM, etc)
Remarks: What makes you suspect that the condition of this monument has changed?

APPENDIX C

MASCOT & GHOST Formats

Please contact ESS for more samples and explanation with MASCOT & GHOST formats. Below samples are provided for reference purposes only.

MASCOT Format Graphical Station Description

CONTROL MONUMENT SKETCH

Mon. No.:	
Replaces:	
Description:	
Intervisible With:	
Mon. No.:	
Replaces:	
Description:	
Intervisible With:	
Mon. No.:	
Replaces:	
Description:	
Intervisible With:	

MASCOT Descriptions of Survey Monuments

```
 Columns   1         2         3         4         5
12345678901234567890123456789012345678901234567890

1990099906120548889192H0829          920606A50
2Brass Tablet in Sidewalk
3                                        Flush
4Sit. in the City of Surrey
4on the S/E corner of Lexington St. & 143rd Ave
4Matson, Peck & Topliss 1999 Survey
```

Line **1** Cols	2- 6	Mascot Project Number
	7-12	Date of Description (yymmdd)
	13-19	GCM of Survey Monument
	20-35	Tablet Marking
	36-41	Date Monument Set
	42-44	Monument Type (Code)

Line **2** 2-81 Description of Monument Type

Line **3** 42-81 Monument Relation to Ground Level

Line **4**

MASCOT Monument Type Codes

Code	**Marker Type**
A01	TYPE 4 CAPPED IRON PIN WITH ALUMINUM DISK
A02	COPPER TACK IN ROOF OF BUILDING
A03	ALUMINUM CAP ON SPREADFOOT BAR
A10	TYPE 1 STANDARD CONCRETE POST WITH VALVE COVER
A11	TYPE 1 STANDARD CONCRETE POST WITH ALUMINUM DISC
A12	TYPE 1 BRASS PLAQUE IN CONCRETE
A13	DEEP BENCH MARK IN MANHOLE
A14	STANDARD CONCRETE POST (PCON)
A20	TYPE 2 STANDARD ROCK POST SET IN ROCK
A30	TYPE 2 STANDARD ROCK POST SET IN CURB
A31	TYPE 4 BCLS PIPE POST
A32	IRON PIPE WITH BRASS CAP
A33	COPPER ROD IN CONCRETE PIER
A40	TYPE 2 STANDARD ROCK POST SET IN GUTTER

A50 TYPE 2 STANDARD ROCK POST SET IN SIDEWALK
A51 TYPE 2 STANDARD ROCK POST SET IN CONCRETE FOUNDATION
A52 TYPE 2 STANDARD ROCK POST SET IN CONCRETE TRAFFIC ISLAND
A53 STANDARD BRASS TABLET SET IN CONCRETE ROADWAY
A60 STANDARD HELIX MARKER
A61 STANDARD HELIX MARKER IN VALVE BOX
A70 TYPE 2 STANDARD ROCK POST SET IN BRIDGE
A80 TYPE 2 STANDARD ROCK POST
A90 BASELINE/BASENET CONCRETE PIER
A91 TRIMBLE GEODETIC L1/L2 ANTENNA MOUNTED ON 4MX7CM STEEL MAST
A92 BROKEN SHANK REMAINING IN ROCK
A93 METAL PLATE
A94 TRIMBLE DOME L1 ANTENNA MOUNTED ON A STEEL MAST
A95 GSC GRAVITY SURVEY ALUMINIUM DISC
B01 CONCRETE PILLAR - 49TH PARALLEL INTERNATIONAL BOUNDARY MONUMENT
B10 RAIL SPIKE
B20 RE-BAR
B30 IRON PIN
B35 8" SPIKE
B40 BRIDGE SPIKE
B50 LEAD PLUG
B60 PUNCH MARK IN EYE BOLT CEMENTED IN ROCK
B81 STEEL BOLT IN CONCRETE BASE
B82 TOP NUT OF FIRE HYDRANT
B83 TOP NUT OF STAND PIPE
H00 TEMPORARY POINT
H05 CHISLE CUT
H10 RAIL SPIKE
H20 RE-BAR
H30 IRON PIN
H31 GALVANIZED BAR
H32 CENTER PUNCH IN ROOF FURNITURE
H40 BRIDGE SPIKE
H50 LEAD PLUG
H60 CENTER PUNCH IN MANHOLE RIM
H70 CONRETE NAIL
H80 8 INCH CARRIAGE BOLT
H82 NAIL
H83 TOP NUT OF STANDPIPE
H84 TOP NUT OF FIRE HYDRANT
H85 THREADED BOLT CEMENTED IN BRICK

GHOST project file – 1

```
GHOST PROJECT FILE 96006
 14 3    1                                                         N
  4     71126                       N49 3917.993080W112 49 8.074440 906.0970
 10
  4    359281                       N49 3839.537280W112 4949.597200 818.6311
  4    554501                       N49 3744.745820W112 4927.324570 913.3631
  4     95547                       N49 3917.690450W112 5049.047970 905.3728
  4    437749                       N49 3840.725520W112 4959.385800 821.6924
  4    369983                       N49 39   .731570W112 4948.420640 826.5384
  4    459842                       N49 3854.970850W112 5014.658360 904.6888
 40
C    24 solutions
C
C DATE: 99-02-21
C SESSION A
C
CGRP  O126281A.052,obs#:     1 day  52                                type  07
C  THE FIXED DOUBLE DIFFERENCE   Session: A
 91GPS
 92    71126                              0.000           0.000           0.000
 92   359281                          -1097.135        -459.312        -836.006
 97PDV UPPER                                                            4.00000
   .101569690000E-04   .453694946000E-05  -.821729706000E-05
   .175309690000E-04  -.110527169900E-04
   .376873210000E-04
CGRP  O126501A.052,obs#:     2 day  52                                type  07
C  THE FIXED DOUBLE DIFFERENCE   Session: A
 91GPS
 92    71126                              0.000           0.000           0.000
 92   554501                          -1209.441       -1878.223       -1860.274
 97PDV UPPER                                                            4.00000
   .100679290000E-04   .441129498000E-05  -.832645968000E-05
   .167199210000E-04  -.102192288000E-04
   .390375040000E-04
CGRP  O126547A.052,obs#:     3 day  52                                type  07
C  THE FIXED DOUBLE DIFFERENCE   Session: A
 91GPS
 92    71126                              0.000           0.000           0.000
 92    95547                          -1869.439         779.880          -6.606
 97PDV UPPER                                                            4.00000
   .879715600000E-05   .386434208000E-05  -.704454660000E-05
   .146842240000E-04  -.931808280000E-05
   .319790250000E-04
CGRP  O501281A.052,obs#:     4 day  52                                type  07
C  THE FIXED DOUBLE DIFFERENCE   Session: A
 91GPS
 92   554501                              0.000           0.000           0.000
 92   359281                            112.306        1418.910        1024.268
 97PDV UPPER                                                            4.00000
   .153585610000E-04   .679421354000E-05  -.132774544300E-04
   .259998010000E-04  -.160700084000E-04
   .620786410000E-04
CGRP  O547281A.052,obs#:     5 day  52                                type  07
C  THE FIXED DOUBLE DIFFERENCE   Session: A
 91GPS
 92    95547                              0.000           0.000           0.000
 92   359281                            772.304       -1239.193        -829.400
 97PDV UPPER                                                            4.00000
   .106732890000E-04   .473969826000E-05  -.896268780000E-05
   .182072890000E-04  -.117060878000E-04
```

GHOST project file – 2

```
   .407044000000E-04
CGRP  0547501A.052,obs#:     6 day  52                                                  type  07
C  THE FIXED DOUBLE DIFFERENCE    Session: A
 91GPS
 92    95547                                      0.000           0.000              0.000
 92    554501                                   659.999       -2658.103          -1853.668
 97PDV UPPER                                                                        4.00000
   .994771600000E-05   .439989308000E-05  -.850485562000E-05
   .168346090000E-04  -.102919652000E-04
   .393254410000E-04
C
C DATE: 99-02-21
C SESSION B
C
CGRP  0501281B.052,obs#:     1 day  52                                                  type  07
C  THE FIXED DOUBLE DIFFERENCE    Session: B
 91GPS
 92    554501                                     0.000           0.000              0.000
 92    359281                                   112.305        1418.906           1024.269
 97PDV UPPER                                                                        4.00000
   .162328410000E-04   .109691942400E-04  -.977145312000E-05
   .321715840000E-04  -.249330910400E-04
   .574412410000E-04
CGRP  0842281B.052,obs#:     2 day  52                                                  type  07
C  THE FIXED DOUBLE DIFFERENCE    Session: B
 91GPS
 92    459842                                     0.000           0.000              0.000
 92    359281                                   344.010        -478.720           -374.364
 97PDV UPPER                                                                        4.00000
   .884467600000E-05   .617732514000E-05  -.567162618000E-05
   .179691210000E-04  -.144533367900E-04
   .333968410000E-04
CGRP  0842501B.052,obs#:     3 day  52                                                  type  07
C  THE FIXED DOUBLE DIFFERENCE    Session: B
 91GPS
 92    459842                                     0.000           0.000              0.000
 92    554501                                   231.706       -1897.626          -1398.633
 97PDV UPPER                                                                        4.00000
   .897601600000E-05   .605431680000E-05  -.538704768000E-05
   .177241000000E-04  -.137204742000E-04
   .315731610000E-04
CGRP  0983281B.052,obs#:     4 day  52                                                  type  07
C  THE FIXED DOUBLE DIFFERENCE    Session: B
 91GPS
 92    369983                                     0.000           0.000              0.000
 92    359281                                  -213.407        -446.102           -430.052
 97PDV UPPER                                                                        4.00000
   .112091040000E-04   .765915264000E-05  -.695526912000E-05
   .227147560000E-04  -.182551144800E-04
   .421460640000E-04
CGRP  0983501B.052,obs#:     5 day  52                                                  type  07
C  THE FIXED DOUBLE DIFFERENCE    Session: B
 91GPS
 92    369983                                     0.000           0.000              0.000
 92    554501                                  -325.712       -1865.008          -1454.321
 97PDV UPPER                                                                        4.00000
   .113232250000E-04   .763182000000E-05  -.678491680000E-05
   .223256250000E-04  -.172678905000E-04
   .397026010000E-04
CGRP  0983842B.052,obs#:     6 day  52                                                  type  07
```

GEOLAB Input File

The following images show a GEOLAB input file (including the constraint equation used for a validation survey), followed by sample extracted adjustment results showing positions and covariances. The GEOLAB input file shows the date and session identifiers used to distinguish each baseline.

GeoLAB Input File Sample

```
*
* Extracted coordinates follow: (extracted on 10:36:32, Mon Aug 23, 1999)
* Source (GeoLab adjustment): Pf96018c
* Variance factor of adjustment = 5.427157
* Variance factor used in computing covariance matrix = 1.000000
* Number of degrees of freedom of adjustment = 54
* Number of stations in adjusted network = 7
* Number of stations extracted = 7
*
3DC
PLH  000 320424        N 53 34   7.74586 W113  2  48.29487      735.735 m     0
PLH  000 388454        N 53 33  53.95050 W112 24  35.78684      687.145 m     0
PLH  000 208595        N 53 34  14.38421 W113 10  25.59555      705.186 m     0
PLH  000 492744        N 53 39  27.22746 W113 11  35.54863      640.193 m     0
PLH  000 421784        N 54  2   9.94000 W113  9  19.16155      637.070 m     0
PLH  000 107797        N 53 35  57.64701 W114 43  13.62264      793.527 m     0
PLH  000 265959        N 53 34  14.43990 W113 11  44.79389      690.650 m     0
COV  LG UPPR
ELEM      5.70906372089991e-06    8.14614661066719e-07   -2.57350261943893e-06
ELEM      4.96958183001199e-06    5.83481966548044e-07   -2.64742768438227e-06
ELEM      2.43221396525738e-06    3.08434080343728e-07    -5.9779332912558e-07
ELEM      2.05466495650321e-06    3.97163406708207e-07   -2.57096657311461e-07
ELEM      4.94610942425514e-06    4.69710895453987e-07    -2.5931392059256e-06
ELEM      4.67956297467959e-06     4.0448656445139e-07   -2.33612887390295e-06
ELEM      9.99997809714891e-07      2.092752852461e-09   -3.08370512500596e-11
ELEM      4.13430540463592e-06    1.48904789023115e-06    4.34442454513483e-07
ELEM      3.65478648512895e-06    1.18894184410723e-06    3.18391890184109e-07
ELEM      1.88175865865362e-06    4.15024629585342e-07    3.83324950276655e-07
ELEM      1.67433459263111e-06    2.13871855485173e-07    4.25384317571148e-07
ELEM      3.62558690026786e-06    1.16025188550353e-06    2.46471714971781e-07
ELEM      3.52581826168388e-06     1.5561444975667e-06   -2.09270272514606e-09
ELEM      9.99996617348682e-07    1.54463151158171e-09
ELEM      8.05395517932108e-06   -2.43843887480012e-06    1.31251853159547e-06
ELEM      7.15177334294414e-06    -6.1945959071939e-07    3.94043749287639e-07
ELEM      2.39989818012361e-06   -2.91235185986603e-07    2.05949799755898e-07
ELEM      1.93059058324373e-06   -2.46782180713336e-06    1.40374640195577e-06
ELEM      7.06696727264695e-06   -2.72359036380575e-06    1.02351319238151e-06
ELEM      6.84872669176728e-06    3.40996350124263e-13   -1.54463041090084e-11
ELEM      9.99998806476344e-09
ELEM      9.60603262139822e-06    2.28117379818385e-07   -5.50411987162403e-07
ELEM      2.19942616655465e-06    2.35064848145041e-07   -6.46593081930446e-07
ELEM      1.86957952792253e-06    2.75674922411043e-07   -2.70988365126114e-07
ELEM      6.36583222537632e-06    2.00155486900028e-07   -1.72329082437923e-06
ELEM       6.0833244623759e-06    3.05145096883262e-07   -1.73218261012933e-06
ELEM      9.99939111735255e-07     1.1034938322352e-08   -5.43905845915203e-11
ELEM      6.28194641839288e-06    1.28797710589369e-06     1.9086334196417le-07
ELEM      1.74419968923666e-06     3.2779050683482e-07    3.08687007308545e-07
ELEM      1.56519565631661e-06    1.81718656750414e-07    3.18675347522121e-07
ELEM      4.40461893062411e-06    1.10736361516916e-06   -5.31638604037515e-08
ELEM      4.32085561931981e-06    1.52053904625947e-06   -1.10341292453301e-08
ELEM       9.9990594519985e-07    8.14547394584495e-09
ELEM      2.65096517436105e-05   -5.98794753202570e-07    3.44277729433588e-07
ELEM      2.11908530567792e-06   -3.49231814209442e-07    1.42415486391248e-07
ELEM      1.68406230749751e-06   -1.88107067077272e-06    1.29285811814152e-06
ELEM      1.43347325112922e-05   -1.89459751288702e-06    9.41023422278819e-07
ELEM      1.38706443774717e-05    1.44301023792307e-12   -8.14444437014031e-11
ELEM      9.99966823051205e-09
ELEM      4.05814852001927e-06    8.82701429498077e-07   -1.41439706483373e-06
ELEM      2.55907597304125e-06    6.57066202996865e-07   -2.89473600529715e-07
ELEM      2.19112909007525e-06    1.94101079689386e-07   -6.26078638348702e-07
ELEM      2.10955854723388e-06    1.99730869306589e-07   -5.78170890928575e-07
ELEM      9.99999522279891e-07   -3.08933854203765e-10    3.34929695362354e-15
ELEM      3.01228385164233e-06    8.04348753358884e-07    6.52096116851178e-07
ELEM      2.02926632013634e-06    3.27570084093915e-07    1.95134215375773e-07
ELEM      1.73454744743739e-06     3.1478733922177e-07    1.11930146282234e-07
ELEM       1.7035368066645e-06    4.12258586465409e-07    3.08933915688187e-10
ELEM      9.99999926285823e-07   -2.28076066545213e-12
ELEM      4.38124062483257e-06   -3.64568883074354e-07    2.75341381476263e-07
ELEM      2.81891784294921e-06   -6.08685998540728e-07    3.69519066504591e-07
ELEM      2.09505875346037e-06   -6.78932673703364e-07     2.6056494236178e-07
ELEM      2.02365755438832e-06   -2.34453071963309e-13    2.28009280807354e-10
ELEM        9.999999739906e-09
ELEM       4.8307897740153e-06    1.61404457146699e-06   -9.95551330766411e-07
```

GeoLab Adjusted Result Output

```
TITL PF96018  (Validation for GPS SOUTH/NORTH 96)
ELIP WGS 84             6378137.0000  6356752.3142      0.0       0.0       0.0
PGEO YES
HIST END ALL RESIDUALS
*******************************************************************************
PLH  000 320424       N 53 34   7.74602 W113  2  48.29245      715.4420
PLH  000 388454       N 53 33  53.95048 W112 24  35.77718      666.8576
PLH  000 208595       N 53 34  14.38443 W113 10  25.59505      684.8835
PLH  000 492744       N 53 39  27.22877 W113 11  35.54887      619.8876
PLH  000 421784       N 54  2   9.94554 W113  9  19.16035      616.7684
PLH  000 107797       N 53 35  57.64750 W114 43  13.63942      773.2210
PLH  000 265959       N53  34 14.44603  W113 11 44.81689  671.082
*******************************************************************************
*******************************************************************************
* Minimal constraint adjustment (ASCM 265959 constrained - 2D/1D)
2DC
PL   000 265959       N 53 34 14.43990  W113 11 44.793890      670.3696
COV  LG DIAG 0.0        1.0       0.0        1.0        0.0
ELEM 1.0E-06                1.0E-06
OHGT     265959                              690.6496         0.0001
*******************************************************************************
* DATE: 96/06/17 DAY 169
* SESS: A
*      2 solutions
GRP  0959454A.169,obs#:    1 day 169                                     type 19
*  THE FIXED DOUBLE DIFFERENCE   Session:  65
3DD
DXYZ      265959       388454         47802.9407   -20647.9411      -379.0206
CORR CT UPPR
ELEM          1.0000000000000        0.3871604800224        -0.4520547389984
ELEM          1.0000000000000       -0.5324527621269
ELEM          1.0000000000000
ELEM            0.00791744422          0.01359336544          0.01527239755
GRP  0959784A.169,obs#:    2 day 169                                     type 19
*  THE FIXED DOUBLE DIFFERENCE   Session:  65
3DD
DXYZ      265959       421784         18916.2982    37414.0911    30551.6607
CORR CT UPPR
ELEM          1.0000000000000        0.2915338277817        -0.4467999637127
ELEM          1.0000000000000       -0.5098538398743
ELEM          1.0000000000000
ELEM            0.00696166093          0.01392624341          0.01555057894
* DATE: 96/06/18 DAY 170
* SESS: A
*      6 solutions
GRP  0424959A.170,obs#:    1 day 170                                     type 19
*  THE FIXED DOUBLE DIFFERENCE   Session:  65
3DD
DXYZ      320424       265959         -9005.1434     4055.1491        86.6234
CORR CT UPPR
ELEM          1.0000000000000        0.3786569535732         0.4002813696861
ELEM          1.0000000000000       -0.3539666533470
ELEM          1.0000000000000
ELEM            0.00462077511          0.00554477563          0.00380359543
GRP  0595424A.170,obs#:    2 day 170                                     type 19
*  THE FIXED DOUBLE DIFFERENCE   Session:  65
3DD
DXYZ      208595       320424          7669.2027    -3472.0784       -97.3248
CORR CT UPPR
ELEM          1.0000000000000        0.3123367726803         0.3384324908257
```

APPENDIX D

Submissions Checklist for Contractors and for ESS

	DESCRIPTION	SECTION	Required	Optional
1	Detailed survey report	3.2	**yes**	
2	Marker Condition Report submitted for each existing station in the project.	3.2		yes
3	MASCOT station descriptions submitted for each new station in the project.	Appendix C	**yes**	
4	Description of how multipath / imaging problems were avoided or mitigated.	2.2		yes
5	Geo-magnetic activity reports from nearest observatory.	2.2		yes
6	Description of how the antenna centering device was checked (tribrach / rangepole).	4.2	**yes**	
7	Detailed GPS Field Logs for each station for every session.	Appendix A	**yes**	
8	Conventional survey notes (if appropriate).		**yes**	
9	Daily diary showing work accomplished, problems encountered, etc.			yes
10	List of all equipment, software, and staff used on the project (make/model/serial numbers/ version numbers).		**yes**	
11	Table showing the GPS observation sessions (showing stations occupied, receiver details, operator name, and actual start/end times for each station).	Appendix A	**yes**	
12	Description of survey design	3.1		yes
13	Description of data handling procedures	5.1		yes
14	Description of baseline processing details (session ID, length (km), duration, ionospheric corrections applied, process controls used, solution type, output quality indicators, comments, etc).	5.1	**yes**	
15	Documentation showing the number of independent occupations at each station, as well as the number of independent baseline connections to each station.		**yes**	
16	Documentation showing all repeat baseline comparisons, and (optionally) loop closure checks.			yes

	Items 17 to 24 concern the LS minimally-constrained adjustment.			
17	Description of LS minimally-constrained adjustment approach (baseline covariance scaling, antenna centering & HI measurement error modelling, fixed station chosen, etc).			yes
18	Description of the baseline adjustment results, including details of any baselines that were rejected, and the impact this has on the network.	5.1	**yes**	
19	Documentation showing the N, E, H residual components for all accepted baselines, indicated if the component was flagged as an outlier. This can be a stand-alone table, or the information can be included in the table described in item 14 above.			yes
20	Description of baseline residual analysis including the aposteriori variance factor.		**yes**	
21	Description of the 95% relative confidence regions analysis.	6.1	**yes**	
22	Table showing the *Local Accuracy* values for each station. These values must meet the project specification(s).	6.4		yes
23	Table showing the coordinate comparisons at existing stations (published values minus the values from the minimally-constrained adjustment for N, E, and H).	5.1, 5.2	**yes**	
24	Description of coordinate comparisons (item 23), identifying any anomalies and steps taken to resolve them.			yes
25	Documentation for constrained adjustment approach and results description, and the derived coordinates for all stations listed in a table.		**yes**	
26	Description of the geoid model and approach used for derivation of orthometric elevations (even if the final elevations are to be established conventionally).	6.2	**yes**	
27	Plan showing all stations and all accepted baselines.	5.2	**yes**	
28	Documentation for stations identified by GCM numbers (digital and hardcopy).		**yes**	
29	All digital and hardcopy submissions listed in Table 1 or Table 2 of this document.		**yes**	
30	**All submissions and results meet ESS standards**		**yes**	

Checked by (ESS): ____________________ *Date:* ______

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