GPS POSITIONING GUIDE

A user's guide to the Global Positioning System

Geomatics Canada
Géomatique Canada

Geodetic Survey Division

Canada

GPS POSITIONING GUIDE

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FOREWORD

The Global Positioning System (GPS), which is scheduled to be fully operational before the end of 1993, will dramatically increase the efficiency and effectiveness of attaining positions for geographically referenced data. The Geodetic Survey Division has been involved with projects using GPS since 1983, providing a solid base of experience.

In 1991, the Economics and Conservation Branch of Environment Canada approached the Geodetic Survey Division seeking support on the application of GPS to groundwater data management in Canada. As a result of discussions, a demonstration project was carried out in the Waterloo area and a "GPS Technology Information Seminar" was presented. As a follow-up, Environment Canada requested that the Geodetic Survey Division produce guidelines for the use of GPS, specific to their needs. Such a document was subsequently prepared for and funded by Environment Canada.

It was realized that most of the information in the document would be equally applicable and important to those in other fields of expertise desiring to apply GPS technology to meet their positioning requirements. Consequently this generalized version of the guidelines on the application of GPS positioning has been produced.

Several individuals within the Geodetic Survey Division have assisted in the development of this document through their comments and suggestions. Their contributions are gratefully acknowledged.

The Geodetic Survey Division has enjoyed the opportunity of sharing its expertise in promoting the application of GPS technology. We hope these guidelines are useful to you. You are encouraged to send your comments and suggestions to us.

Caroline Erickson
Geodetic Survey Division
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INTRODUCTION

The Global Positioning System (GPS), which is scheduled to be fully operational before the end of 1993, will dramatically increase the efficiency and effectiveness of establishing geodetic or geographically referenced control. The Geodetic Survey Division of Geomatics Canada has performed [illegible] projects using GPS since 1985, providing a solid base of experience.

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[illegible] the application of GPS [illegible] publication.

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The Geodetic Survey Division [illegible] in preparing [illegible] useful to you [illegible] comments and suggestions to [illegible]

[illegible]
Director
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NOTATION & ACRONYMS

1D	one dimensional
2D	two dimensional
2drms	two times distance root mean square
3D	three-dimensional
ACP	Active Control Point
ACS	Active Control System
AS	anti-spoofing
Az.	azimuth
c	speed of light in a vacuum
CCM	Canada Centre for Mapping, Energy Mines and Resources, Canada
CDU	control and display unit
CEP	circular error probable
CGD	Canadian Geodetic Datum 1928
DoD	United States Department of Defense
DOP	dilution of precision
DoT	United States Department of Transportation
EDM	electronic distance measurement
Elev.	elevation angle
EMR	Energy, Mines and Resources Canada
f	frequency
Φ	measured carrier phase
GDOP	geometrical dilution of precision
GIS	geographical information system
GPS	Global Positioning System
GPSIC	Global Positioning System Information Center
GSD	Geodetic Survey Division, Energy Mines and Resources Canada
GSD91	Geodetic Survey Division 1991 geoid model
h	ellipsoidal height
H	orthometric height
HDOP	horizontal dilution of precision
Hz	hertz (cycles per second) - unit of measure for frequency

IERS	International Earth Rotation Service
ITRF91	IERS Terrestrial Reference Frame
λ	wavelength
MHz	one million hertz (see Hz)
MSE	mean square error
N	ambiguity, or
N	geoid undulation
NAD27	North American Datum 1927
NAD83	North American Datum 1983
NGDB	National Geodetic Database (maintained by GSD)
NGS	U.S. National Geodetic Survey
NTS	National Topographic System
P	code measurement
PDOP	positional dilution of precision
ppm	parts per million
ρ	range
rcvr	receiver
RF	radio frequency
RINEX	receiver independent exchange format
rms	root mean square
σ	standard deviation
SA	selective availability
SEP	spherical error probable
SMRSS	Surveys, Mapping and Remote Sensing Sector
t_r	reception time
t_t	transmission time
UERE	user equivalent range error
UTM	Universal Transverse Mercator Projection
VDOP	vertical dilution of precision
WGS84	World Geodetic System 1984
x_r, y_r, z_r	receiver coordinates
x^s, y^s, z^s	satellite coordinates

CHAPTER 1
INTRODUCTION

The Global Positioning System (GPS) is a satellite-based radio-navigation system established by the U.S. Department of Defense for military positioning applications and as a by-product, has been made available to the civilian community. Navigation, surveying and integration with Geographic Information Systems (GIS) are just a few of the fields which have seen the successful application of GPS technology.

GPS is a complex system which can be used to achieve position accuracies ranging from 100 m to a few millimetres depending on the equipment used and procedures followed. In general, higher accuracies correspond with higher costs and more complex observation and processing procedures. Therefore it is important for users to understand what techniques are required to achieve desired accuracies with the minimal cost and complexity. The objective of these guidelines is to provide the background and procedural information needed to effectively apply GPS technology.

These guidelines contain four main parts geared towards achieving this objective. The fundamentals of GPS are explained in Chapter 2, basic positioning concepts are presented in Chapter 3, GPS positioning techniques are described in Chapter 4 and procedures for the application of GPS are discussed in Chapter 5. Although there are significant links between each of these chapters, one may prefer to reference any segment of these guidelines individually with the aid of the Table of Contents.

The fundamental GPS concepts presented in Chapter 2 provide a starting point for those seeking to gain a better understanding of what GPS is all about. The discussion of GPS signals in this chapter is of particular importance since it is these signals which are at the root of the varied positioning techniques and their associated accuracies. The other concepts presented in Chapter 2 include a description of the system, general classifications of the types of GPS positioning, satellite visibility and errors.

The significance of the basic positioning concepts presented in Chapter 3 should not be underestimated. An awareness of the various measures of accuracy used with respect to GPS is essential if one hopes to compare what is achievable with different techniques and equipment. A positioning concept of particular importance is the difference in the height system used by GPS satellites and the commonly used mean sea level heights. This is presented in Chapter 3 along with a description of coordinate systems and datums.

Perhaps what might be the most interesting for those desiring to apply GPS are the positioning techniques summarized in Chapter 4. The beginning of the chapter commences by tabulating representative accuracies which can be achieved if the designated technique is successfully applied. Descriptions of each of these techniques follow. When reviewing these techniques, one should note that new methods are continually under development. An understanding of the general concepts of the methods presented herein, should make it easier to understand new techniques as they become available.

The final chapter deals with procedures for carrying out a GPS project from initial conception to final returns. Since every project to be carried out and each set of equipment will require different procedures it would be impossible to address all contingencies in this chapter. Instead, general considerations and procedures which would be common to almost any GPS positioning project are presented. For specific detailed instructions one is wise to consult with manufacturers' documentation. The last section of Chapter 5 addresses special considerations which must be made when determining elevations with GPS.

The appendices of these guidelines also provide a wealth of information. They include a glossary for all the terms included in the main portion of the text which are in italics, sources of information which may be beneficial when carrying out a GPS project, and suggested reading to learn more about GPS and its uses.

A set of guidelines such as these cannot hope to address all queries regarding the huge and rapidly expanding industry of positioning with GPS. However it is hoped that they will help users appreciate the incredible benefits of the system and successfully employ it to satisfy their positioning needs.

CHAPTER 2

GPS - BASIC CONCEPTS

In this chapter, basic concepts of the Global Positioning System are presented. GPS can provide a wide range of accuracies, depending on the type of measurements used and procedures followed. In general, the higher the accuracy required, the higher the cost and the greater the complexity of using GPS. For users to understand which techniques are most suited for their requirements and why, it is important that the basic underlying concepts of GPS are understood. The main segments of GPS are described, followed by an explanation of GPS satellite signal components, general positioning techniques, satellite visibility and GPS error sources.

2.1 SYSTEM DESCRIPTION

The Global Positioning System (GPS) consists of a constellation of radio-navigation satellites, a ground control segment which manages satellite operation and users with specialized receivers who use the satellite data to satisfy a broad range of positioning requirements (Figure 2.1). The system was established by the United States Department of Defense (DoD) to fulfill defence positioning needs and as a by-product, to serve the civilian community.

The *satellite constellation*, which is expected to be fully operational by the end of 1993, will consist of 21 satellites and three active spares positioned 20,000 km (about three times the earth's radius) above the earth. The satellites will be distributed in a manner that ensures at least four satellites are visible almost anywhere in the world at any time (Figure 2.2). Each satellite receives and stores information from the control segment, maintains very accurate time through on-board precise atomic clocks and transmits signals to the earth.

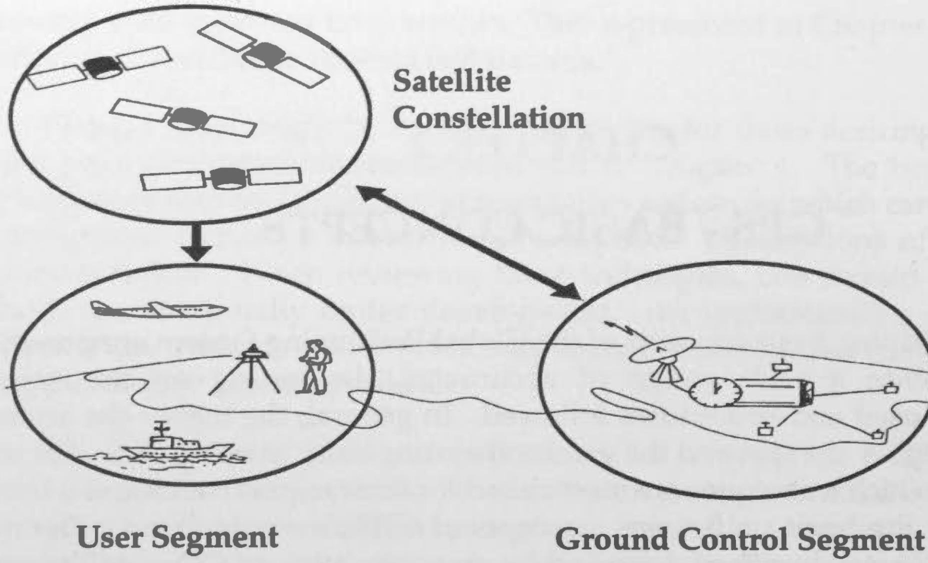


Figure 2.1 Three Segments of GPS

The *ground control segment* (Figure 2.1) operates the satellite system on an on-going basis. It consists of five tracking stations distributed around the earth of which one, located in Colorado Springs, is a Master Control Station. The control segment tracks all satellites, ensures they are operating properly and computes their position in space.

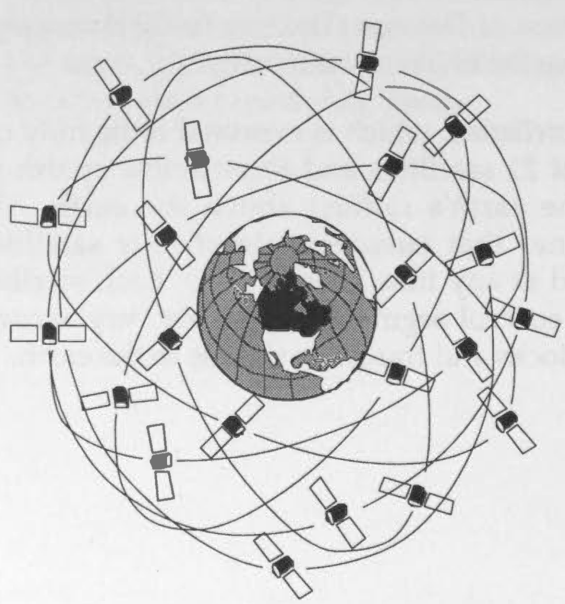


Figure 2.2 GPS Satellite Constellation

If a satellite is not operating properly the ground control segment may set the satellite "unhealthy" and apply measures to correct the problem. In such cases, the satellite should not be used for positioning until its status is returned to "healthy". The computed positions of the satellites are used to derive parameters, which in turn are used to predict where the satellites will be later in time. These parameters are uploaded from the control segment to the satellites and are referred to as *broadcast ephemerides*.

The *user segment* includes all those who use GPS tracking equipment to receive GPS signals to satisfy specific positioning requirements. A wide range of equipment designed to receive GPS signals is available commercially, to fulfill an even wider range of user applications. Almost all GPS tracking equipment have the same basic components: an antenna, an RF (radio frequency) section, a microprocessor, a control and display unit (CDU), a recording device, and a power supply. These components may be individual units, integrated as one unit, or partially integrated (Figure 2.3). Usually all components, with the exception of the antenna, are grouped together and referred to as a receiver. Some GPS receivers being marketed now in fact only consist of computer cards which may be mounted in portable computers or integrated with other navigation systems.

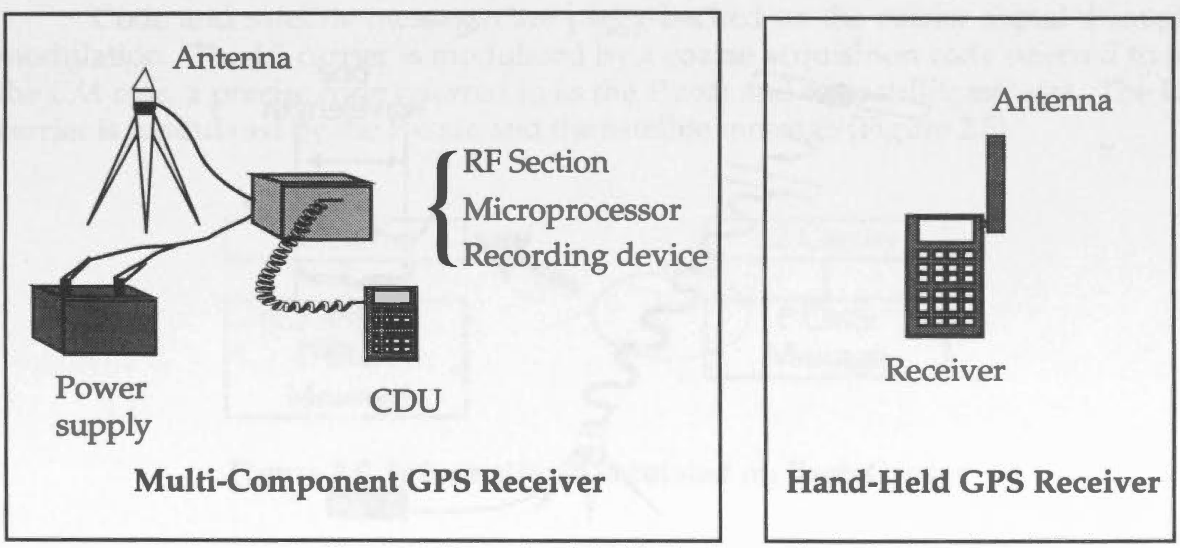


Figure 2.3 GPS Equipment

2.2 GPS SIGNALS

Each GPS satellite continuously transmits signals which contain a wealth of information. Depending on the type and accuracy of positioning being carried out, a user may only be interested in a portion of the information included in the GPS signal. Similarly, a given GPS receiver may only enable use of a portion of the available information. It is therefore important for users to understand the content and use of GPS signals. The information contained in GPS signals includes the carrier frequencies, Coarse Acquisition (C/A) and Precise (P) codes and the satellite message. Descriptions of each of these signal components follow.

Carrier Measurements

Signals from GPS satellites are continuously transmitted on two *carrier frequencies*, 1575.42 MHz and 1227.60 MHz, and are referred to as L1 and L2 respectively. Since radio waves propagate through space at the speed of light, the wavelengths of the GPS carrier signals are computed as

$$\lambda = c / f \tag{2.1}$$

where λ is the wavelength (i.e. the length of one cycle) in metres, c is the speed of light (approximately 3×10^8 m/s) and f is the carrier frequency in Hz (i.e. cycles per second). A snapshot of one section of carrier transmission which illustrates the definition of wavelength and cycles is shown in Figure 2.4.

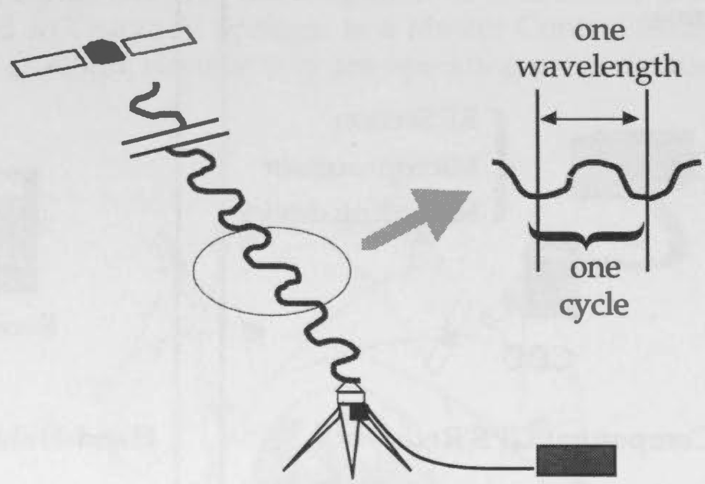


Figure 2.4 Carrier

The frequency and wavelength of the L1 and L2 carriers (computed using equation (2.1)) are given in Table 2.1.

GPS receivers which record carrier phase, measure the fraction of one wavelength (i.e. fraction of 19 cm for the L1 carrier) when the receiver first locks onto a satellite and continuously measure the carrier phase from that time. The number of cycles between the satellite and receiver at initial start up (referred to as the *ambiguity*) and the measured carrier phase together represent the satellite-receiver range (i.e. the distance between a satellite and a receiver). In other words,

measured carrier phase = range + (ambiguity × wavelength) + errors

or $$\Phi = \rho + N\lambda + \text{errors}, \quad (2.2)$$

where Φ is the measured carrier phase in metres, ρ is the satellite-receiver range in metres, N is the *ambiguity* (i.e. number of cycles) and λ is the carrier wavelength in metres. Note that a sign convention similar to that adopted by the Canadian GPS Associates (Wells et.al.) was used. The errors are as described in Section 2.5.

Table 2.1 Carrier Frequencies and Wavelengths

Carrier	Frequency (f)	Wavelength (λ)
L1	1575.42 MHz	19 cm
L2	1227.60 MHz	24 cm

Code and satellite messages are piggy-backed on the carrier signal through modulation. The L1 carrier is modulated by a coarse acquisition code referred to as the *C/A code*, a precise code referred to as the *P code* and the *satellite message*. The L2 carrier is modulated by the P code and the satellite message (Figure 2.5).

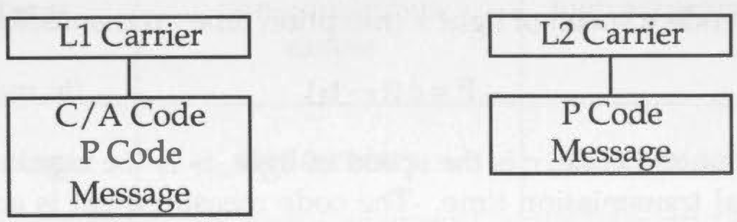


Figure 2.5 Information Modulated on Each Carrier

Code Measurements

It is the code measurements (also referred to as pseudorange measurements) that enable instantaneous position determinations using GPS satellites. The code is composed of a series of chips which have values of 1 or 0. The C/A code has a frequency of 1.023 MHz (i.e. 1.023 million chips per second) and the P code has a frequency of 10.23 MHz. Example portions of C/A code and P code are shown in Figure 2.6.

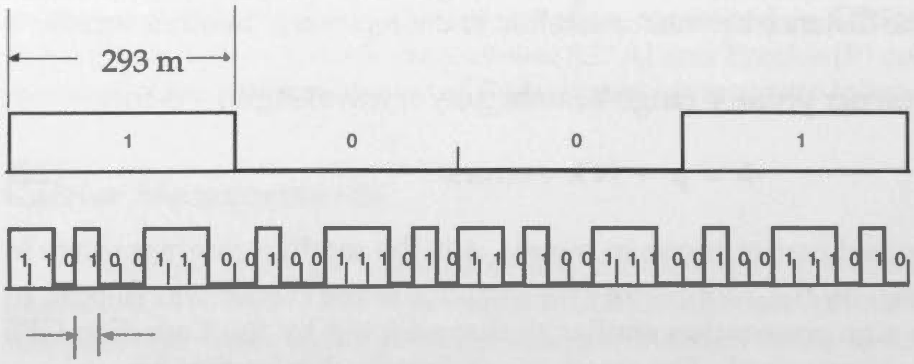


Figure 2.6 C/A and P Codes

The chip lengths of 293 m and 29.3 m for the C/A code and P code respectively were computed using equation (2.1), letting λ be the chip length. Although the P code is generally ten times more accurate than the C/A code, it is expected to be unavailable for civilian use in 1993 when the full GPS constellation is complete (McNeff, 1991), meaning only C/A code is worthy of consideration for civilian GPS applications.

Code measurements are the difference in time between when the code is transmitted from a satellite and received at a GPS receiver, multiplied by the speed of light. That is,

measured code = speed of light × (reception time - transmission time)

or $$P = c\,(t_r - t_t). \qquad \text{(in metres)} \qquad (2.3)$$

where P is the measured code, c is the speed of light, t_r is the signal reception time and t_t is the signal transmission time. The code measurement is actually a direct measurement of satellite=receiver range (ρ), i.e.:

measured code = range + errors

or $$P = \rho + \text{errors}. \qquad \text{(in metres)} \qquad (2.4)$$

The errors are as described in Section 2.5.

Comparison of Code and Carrier Measurements

At this point it is possible to make some brief comparisons of code and carrier measurements. Carrier wavelengths (19 cm for L1) are much shorter than the C/A code chip length (293 m) and consequently can be measured more accurately and used to achieve much higher positional accuracies than code measurements. Indeed the best relative accuracies achieved using code measurements are usually a few metres, and using carrier measurement are usually a few centimetres.

The problem with using carrier observations instead of code observations is evident upon comparison of equations (2.2) and (2.4). With code observations a direct measure of the satellite–receiver range is attained. With carrier observations, the ambiguity term (number of whole cycles) must be estimated before one may take advantage of the carrier accuracy. Ambiguity estimation leads to complexities in the use of carrier phase observations which do not exist with code observations. The advantages and disadvantages of code and carrier observations are summarized in Table 2.2.

Table 2.2 Key Advantages and Disadvantages of Code and Carrier Observations

	Code	**Carrier**
Advantages	non-ambiguous simple	high accuracy potential
Disadvantages	low accuracy	more complex

Satellite Message

The satellite message, which is modulated on both L1 and L2 frequencies, contains among other information, satellite broadcast ephemerides and health status. The ephemerides include the parameters necessary to compute a satellite's position in space for a given time and the health status indicates if a satellite is healthy. Almost all receivers use the broadcast ephemerides in conjunction with code observations, carrier observations or both to solve for a GPS receiver's position in space.

2.3 TYPES OF GPS POSITIONING

Up to this point, the three segments of GPS have been described and the components of signals broadcasted by the satellites have been explained. Major types of possible positioning methods may now be defined. Note that only broad definitions are presented here, while specific GPS positioning methods are addressed in Chapter 4.

Single Point versus Relative Positioning

Positioning with GPS may take the form of *single point positioning* or *relative positioning*. In single point positioning coordinates of a receiver at an "unknown" point are sought with respect to the earth's reference frame by using the "known" positions of the GPS satellites being tracked. Single point positioning is also referred to as *absolute positioning*, and often just as *point positioning*. In relative positioning the coordinates of a receiver at an "unknown" point are sought with respect to a receiver at a "known" point.

The concept of single point positioning is illustrated in Figure 2.7. Using the broadcast ephemerides, the position of any satellite at any point in time may be computed.

In the figure, s1, s2, s3 and s4 represent four different satellites being tracked. The positions of these satellites are referenced to the centre of the earth in the x,y,z coordinate frame. The coordinates for s1 are shown as (x^{s1}, y^{s1}, z^{s1}). The coordinates of r, the unknown point, as referenced to the centre of the earth, are (x_r, y_r, z_r). The observed code, P_r^{s1}, relates the known coordinates of satellite 1 with the unknown coordinates of the receiver shown in Figure 2.7 using the equation for a line in three-dimensional space. That is,

$$P_r^{s1} = \sqrt{(x^{s1} - x_r)^2 + (y^{s1} - y_r)^2 + (z^{s1} - z_r)^2} + \text{errors}. \qquad (2.5)$$

The same equation showing the relation between satellite 1 and the receiver may be formed for all satellites tracked. With at least four satellites all the unknowns (x_r, y_r, z_r and a clock term which forms part of the errors) may be computed.

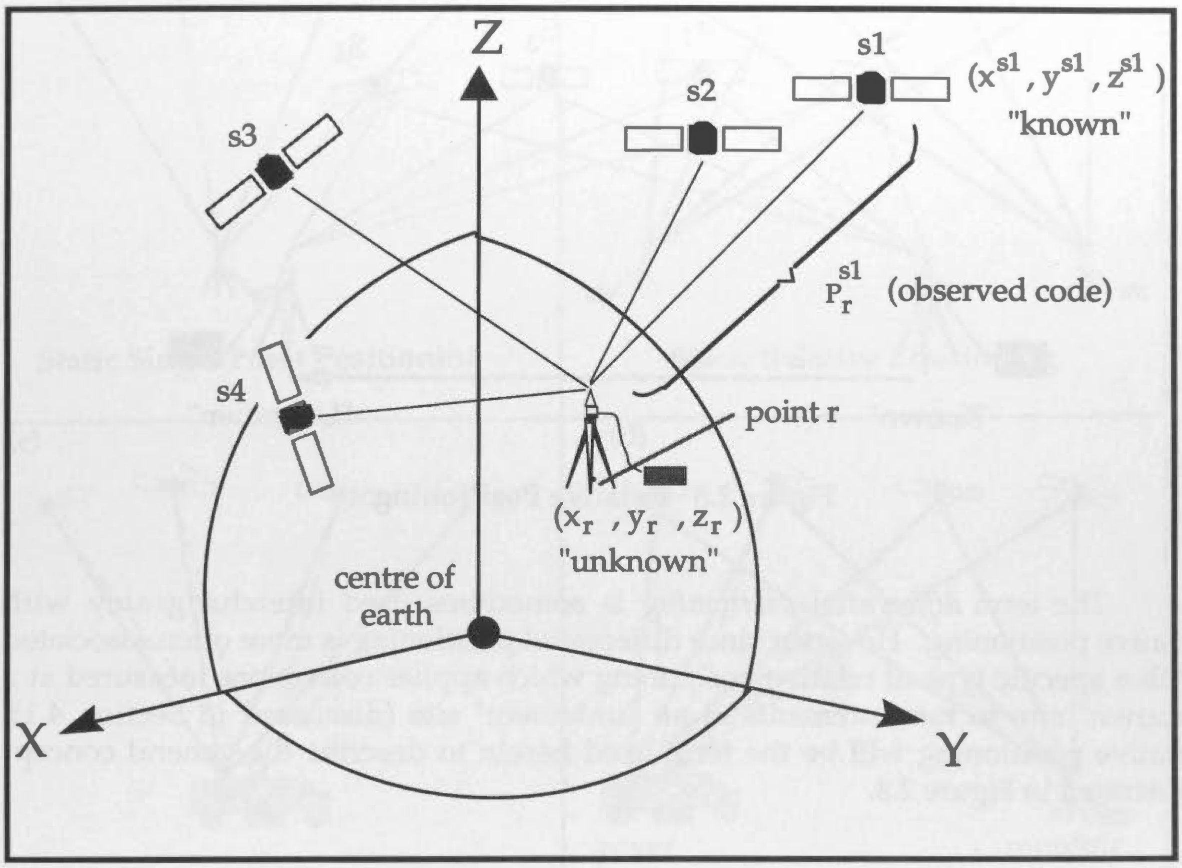


Figure 2.7 Single Point Positioning

The concept of relative positioning is illustrated in Figure 2.8. Instead of determining the position of one point on the earth with respect to the satellites (as done in single point positioning), the position of one point on the earth is determined with respect to another "known" point. The advantage of using relative rather than single point positioning is that much higher accuracies are achieved because most GPS observation errors are common to the known and unknown site and are reduced in data processing.

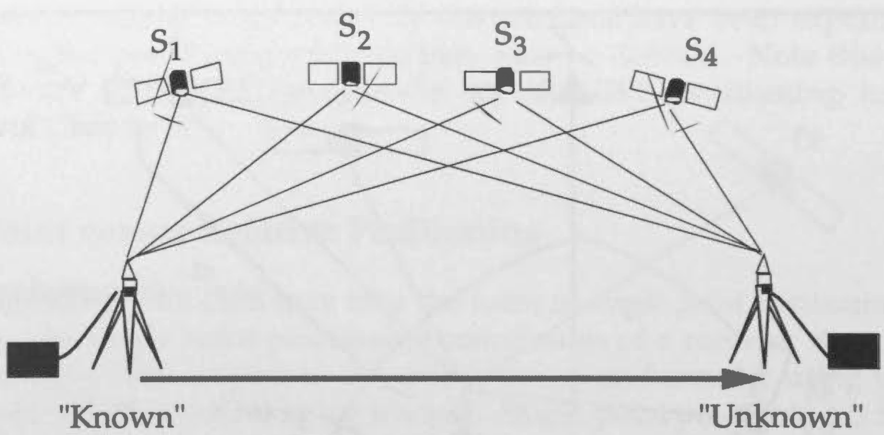


Figure 2.8 Relative Positioning

The term *differential positioning* is sometimes used interchangeably with relative positioning. However since differential positioning is more often associated with a specific type of relative positioning which applies corrections measured at a "known" site to measurements at an "unknown" site (discussed in Section 4.1), relative positioning will be the term used herein to describe the general concept illustrated in Figure 2.8.

Static versus Kinematic Positioning

GPS positioning may also be categorized as *static* or *kinematic*. In static positioning, a GPS receiver is required to be stationary whereas in kinematic positioning a receiver collects GPS data while moving. The concepts of static and kinematic positioning for both single point and relative positioning cases are illustrated in Figure 2.9. Note that for kinematic relative positioning one receiver, referred to as a *monitor*, is left stationary on a known point while a second receiver, referred to as a *rover*, is moved over the path to be positioned.

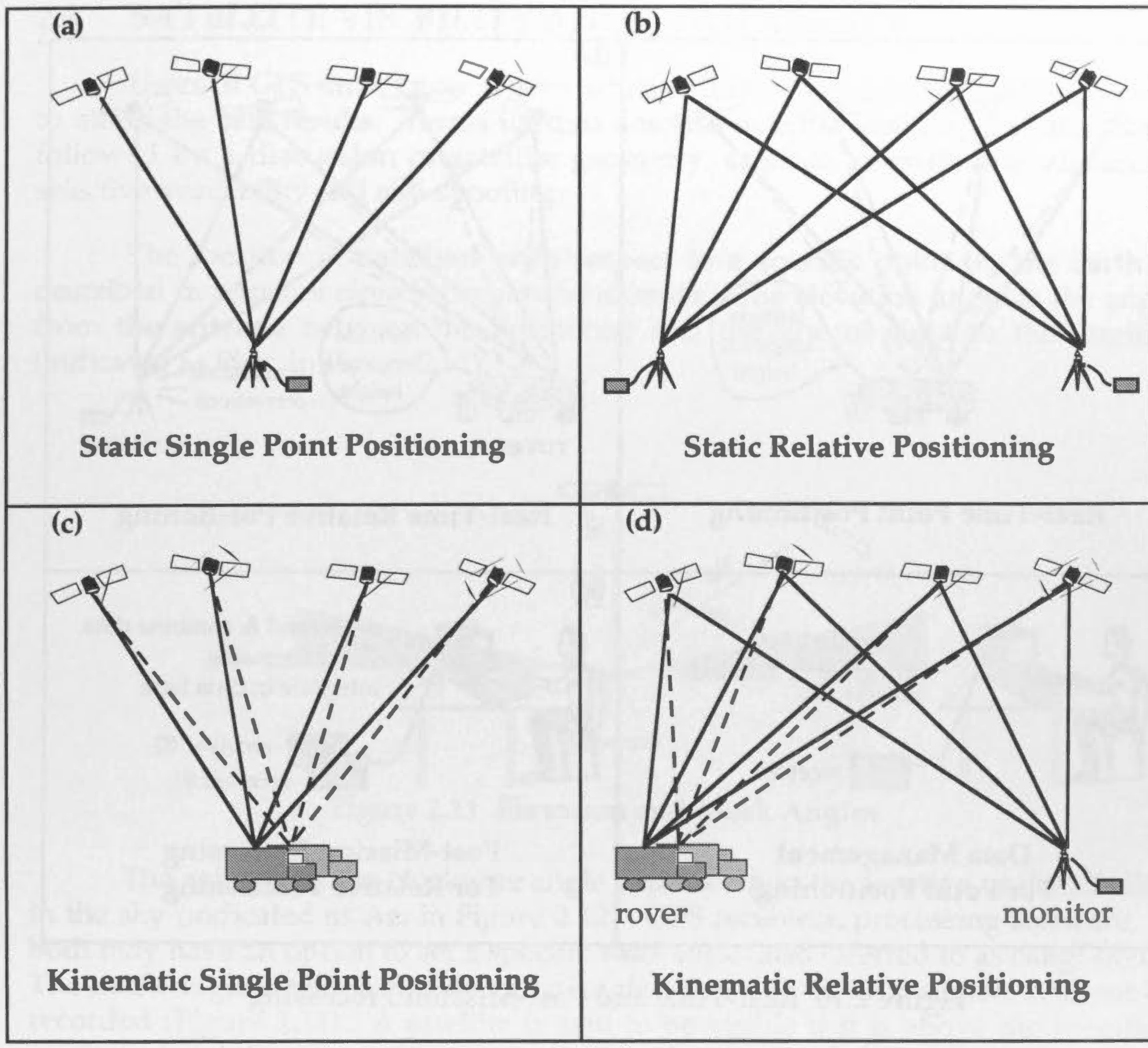


Figure 2.9 Static and Kinematic Positioning

Real-Time versus Post-Mission

GPS positions may be attained through *real-time* or *post-mission processing* (Figure 2.10). In real-time processing, positions are computed almost instantaneously, on site. In post-mission processing, data is combined and reduced after all data collection has been completed. *Real-time relative positioning* requires a data link to transmit corrections from a monitor receiver at a known point to a rover receiver at an unknown point (Figure 2.10b). Post-mission processing for relative positioning requires physically bringing together the data from all receivers after an observation period (Figure 2.10d). Even with real-time point positioning, for many GPS applications it is still necessary to download data and enter it in a database specific to the user's application (Figure 2.10c).

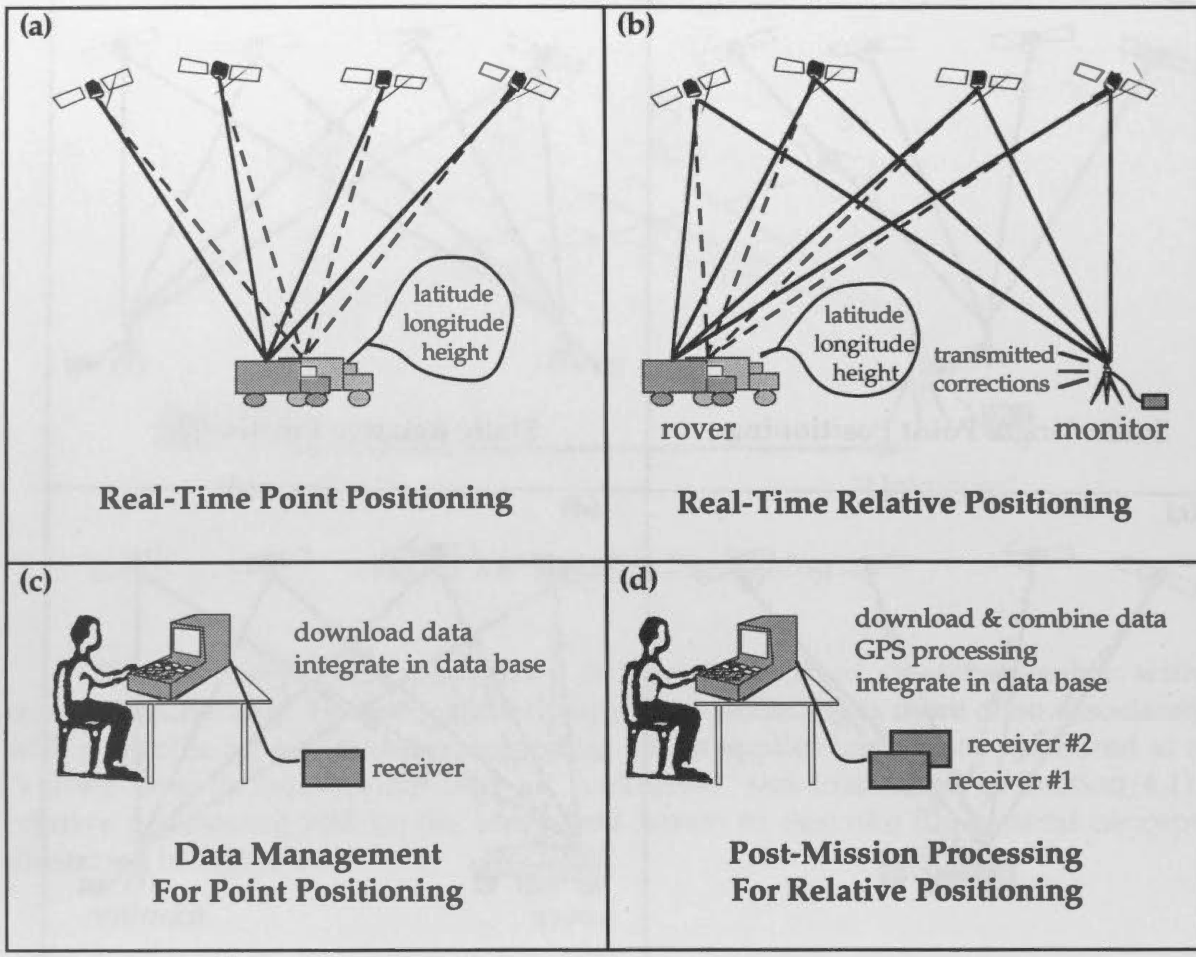


Figure 2.10 Real-Time and Post-Mission Processing

Very low accuracy code single point positioning is usually computed by GPS receivers in real-time, whereas very high accuracy carrier relative positioning is almost always dependent on post-mission processing. Real-time and post-mission processing options exist for methodologies which yield accuracies between these two extremes.

All GPS positioning may be classified as static or kinematic, single point or relative, and real-time or post-mission. In Chapter 4, specific types of GPS positioning methodologies are presented, but each of these may also be categorized using the above terminology. All users of GPS, no matter what the positioning type used, must be aware of the best times for data collection, which brings about discussion of satellite visibility and availability.

2.4 SATELLITE VISIBILITY AND AVAILABILITY

Users of GPS must know where, when and what satellites should be tracked to attain the best results. Terms used to describe satellite visibility are described, followed by a discussion of satellite geometry, satellite azimuth and elevation, selective availability and anti-spoofing.

The location of satellites with respect to a specific point on the earth is described in terms of *elevation angle* and *azimuth*. The elevation angle is the angle from the antenna between the horizontal and the line of sight to the satellite (indicated as Elev. in Figure 2.11).

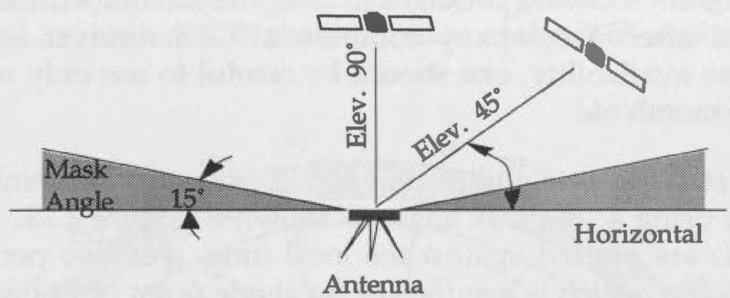


Figure 2.11 Elevation and Mask Angles

The azimuth is the clockwise angle from north to the location of the satellite in the sky (indicated as Az. in Figure 2.12). GPS receivers, processing software, or both may have an option to set a specific *mask angle* (also referred to as *cutoff angle*). The mask angle refers to the elevation angle below which GPS signals will not be recorded (Figure 2.11). A satellite is said to be visible if it is above the specified mask angle for the time and location of interest assuming no *obstructions* are present.

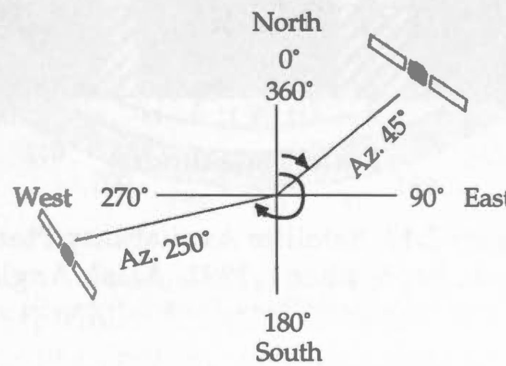


Figure 2.12 Azimuth

Obstructions are objects which block the path between a satellite and receiver. For example, if a desired satellite is at an elevation of 20 and azimuth of 70 , and a building is located at the same elevation and azimuth, the satellite signal will be obstructed. The avoidance of obstructions is very important to the successful application of GPS positioning.

For any given location on the earth, and any given date and time, it is possible to predict which satellites will be available and their location in the sky. This is accomplished by using *almanac files* which contain satellite orbit parameters, in conjunction with software designed to use almanac files to compute satellite visibility. Current almanac files are available from the GPS Information Center and Hollman GPS Bulletin Board Service (see Appendix B for details). Many receivers display satellite availability information while tracking, provide almanac files for downloading, or both. Software packages to compute satellite visibility are available commercially and often accompany commercial GPS receiver software. When computing satellite availability, one should be careful to use only recent almanacs, no more than one month old.

A sample satellite availability plot for 12 hours on September 1st 1992, at Waterloo Ontario using a 15 mask angle, is shown in Figure 2.13. The number of satellites available are plotted against the local time. For two periods only three satellites are available, which is insufficient for single point positioning. For a short period (between 7 and 8 hours) six satellites are available, which is favourable since in general the more satellites, the better the chance of success with GPS positioning.

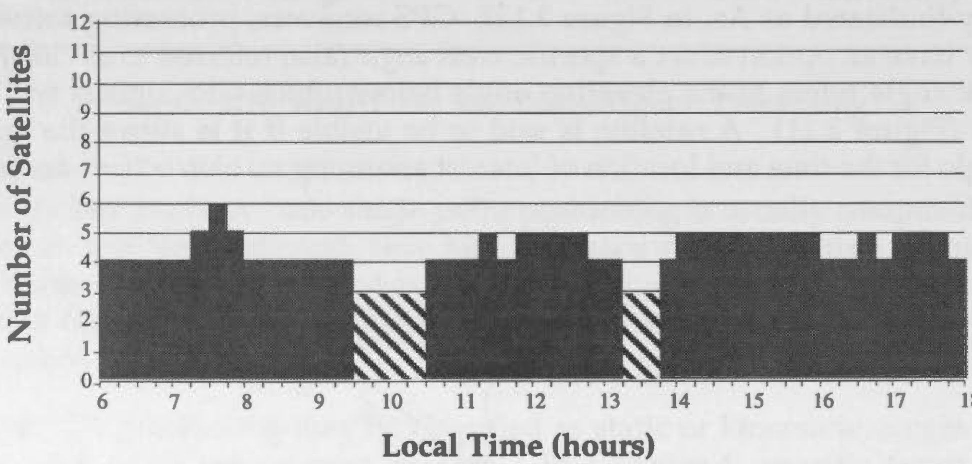


Figure 2.13 Satellite Availability Plot
Waterloo , September 1, 1992, Mask Angle 15
(based on Ashtech Mission Planning Software)

Satellite coverage repeats itself from day to day, but appears four minutes earlier. This means the satellite visibility plot for September 2 would be identical to that for September 1 (Figure 2.13) but shifted four minutes to the left. The satellite visibility plot for September 8 (one week later) would be shifted about one half hour to the left, and for October 1 (one month later) would be shifted about two hours to the left.

Satellite Geometry

Sometimes sky plots, as illustrated in Figure 2.14, are used to represent satellite visibility. To interpret such plots, one must imagine being situated at the centre of the plot. Each concentric ring represents an elevation angle, while each radiating line represents an azimuth. In the figure, the shaded area, below 15 elevation represents the mask angle. The path of all visible satellites over a two hour period is plotted. The numbers indicated on each plotted line are the satellite numbers. For example, satellite 13 is shown in the plot as tracing a path from an elevation of 40 and azimuth of 270 to an elevation of about 63 and azimuth of 10 .

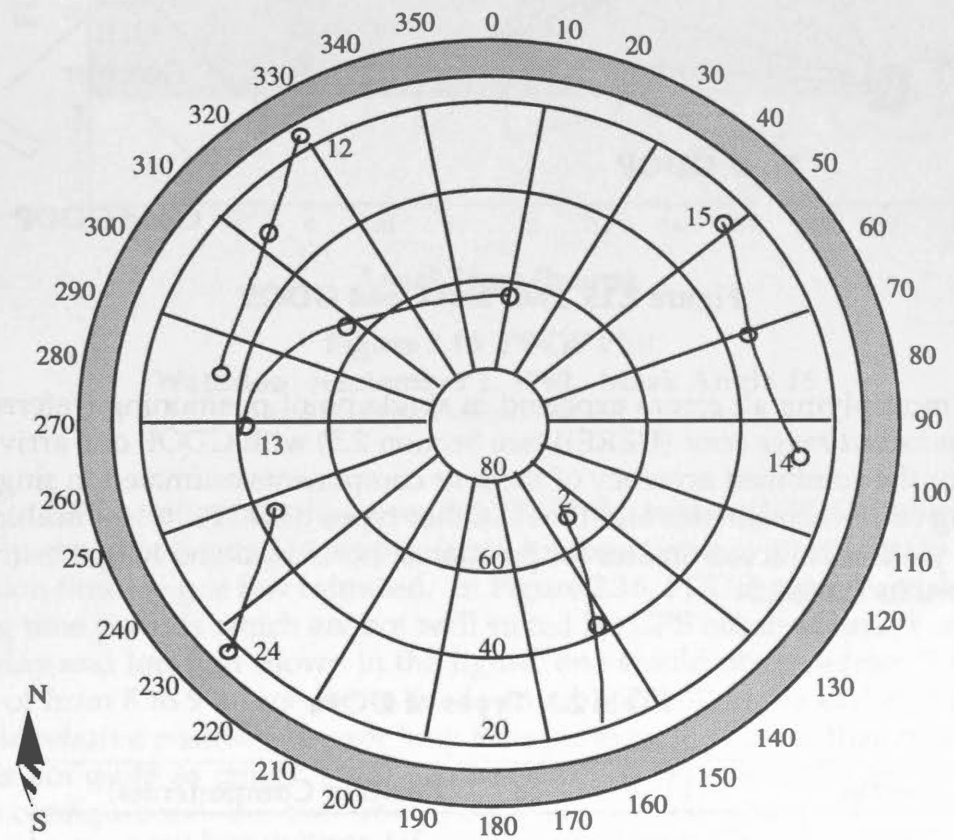


Figure 2.14 Sky Plot
Waterloo , September 1, 1992, 11h to 13h, Mask Angle 15
radial lines represent azimuths, concentric rings represent elevations
(based on Ashtech Mission Planning Software)

Satellite geometry has a direct effect on positioning accuracies. The best single point positioning accuracies are achieved when satellites have good spatial distribution in the sky (e.g. one satellite overhead and the others equally spread horizontally and at about 20 elevation). Sub-optimal geometry exists when satellites are clumped together in one quadrant of the sky. The geometry of satellites, as it contributes to positioning accuracy, is quantified by the geometrical *dilution of precision* (GDOP). Satellite configurations exemplifying poor and good GDOP are illustrated in Figure 2.15.

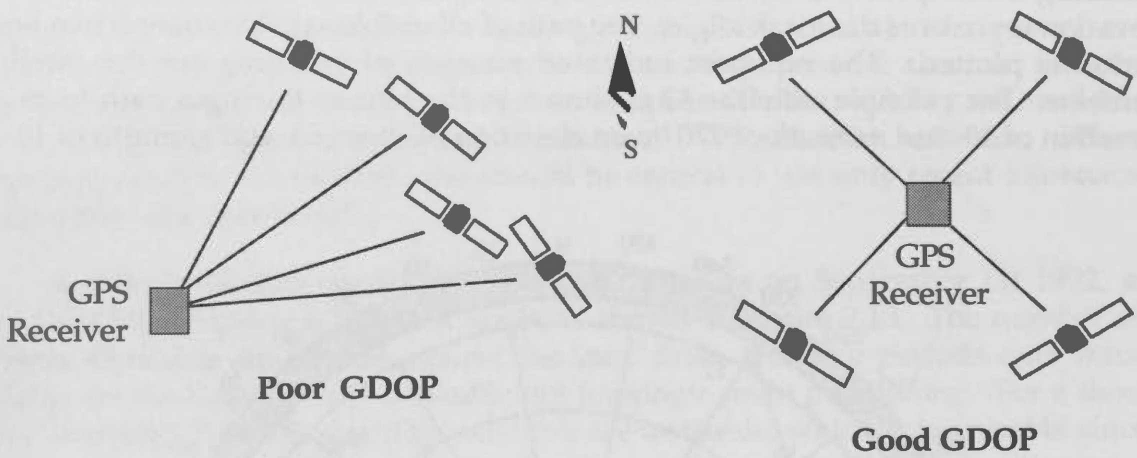


Figure 2.15 Poor and Good GDOP

By multiplying all errors expected in single point positioning (referred to as the *user equivalent range error* (UERE)) (see Section 2.5) with GDOP one arrives at an estimate for the combined accuracy of the four components estimated in single point positioning (three coordinates and time). Other types of DOPs, when multiplied by the UERE yield accuracy estimates for positional, horizontal and height estimates as summarized in Table 2.3.

Table 2.3 Types of DOPs

Acronym	Type	Position Component(s)
GDOP	Geometrical	3D position and time
PDOP	Positional	3D position
HDOP	Horizontal	2D horizontal position
VDOP	Vertical	1D height

Most GPS software packages include the ability to compute DOPs before an observation period. The information needed to compute DOPs is the same as that required to compute the satellite availability and sky plots of Figures 2.13 and 2.14 (i.e., a recent almanac file, approximate latitude and longitude, the date and the time period). Figure 2.16 shows PDOPs which correspond to the same time and location as the plot for the number of available satellites in Figure 2.13. Note there is a general tendency for low PDOPs with an increased number of satellites and vice versa.

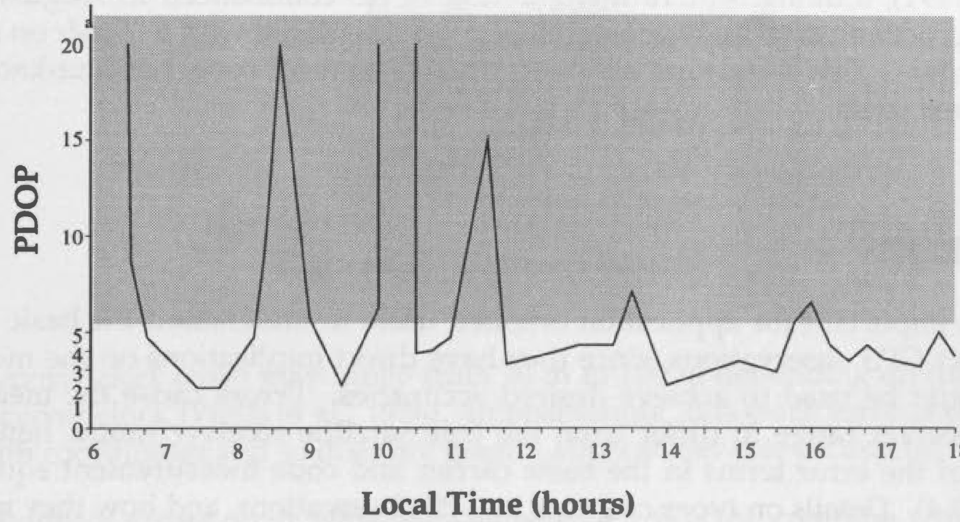


Figure 2.16 PDOP Plot
Waterloo , September 1, 1992, Mask Angle 15
(based on Ashtech Mission Planning Software)

For GPS positioning, the lower the PDOP the better. A PDOP below 5 or 6 is generally the recommended upper limit for positioning, particularly for short occupation times (e.g. a few minutes). In Figure 2.16, PDOPs over 6 are shaded out, showing time periods which are not well suited for GPS observations. For example, for the day and location shown in the figure, one would observe from 7 to 8 hours instead of from 8 to 9 hours due to the favourable PDOP in the earlier time period. For static relative positioning over long time periods, (e.g. more than one hour) the PDOP is not quite as critical since one benefits not only from the geometry of the satellite configuration, but also from the geometry of the path the satellites trace in the sky over time.

Selective Availability and Anti-Spoofing

Two terms often associated with GPS status are *selective availability* (SA) and *anti-spoofing* (AS). Both refer to techniques to limit the accuracies achievable for civilian users. Selective availability consists of the degradation of the broadcast orbit (i.e. the accuracy of the satellites' "known" position in space) and dithering of the satellite clocks. SA is currently being implemented. As a result of SA, single point positioning accuracies are limited to 100 m horizontally and 156 m vertically at the 95% confidence level (U.S. DoD and DoT, 1986), instead of the 20-30 m and 30-45 m possible without SA (Cannon, 1991).

Anti-spoofing is the denial of access of the P code to civilian users (except those with special authorization from the U.S. DoD). Implementation of AS is planned to begin when the full GPS constellation is available at the end of 1993 (McNeff, 1991), although intermittent testing of AS commenced in August 1992. When AS is activated, to deny access, the P code is replaced with a *Y code* on the L1 and L2 carriers. This Y code has similar properties to the P code, but is unknown to unauthorized users.

2.5 ERRORS

It is important for application oriented users to understand the basic errors which affect GPS observations, since they have direct implications on the methods which should be used to achieve desired accuracies. Errors cause the measured satellite-receiver range to differ from the true satellite-receiver range, hence the inclusion of the error terms in the basic carrier and code measurement equations (2.2) and (2.4). Details on types of errors in GPS observations, and how they may be handled are described in several publications (e.g. Wells et al., 1986; Lachapelle, 1991) and are briefly discussed here.

Errors which influence GPS range measurements are illustrated in Figure 2.17. The *orbital error* refers to the difference between the satellite position as calculated using the broadcast ephemerides and the "true" position of a satellite in space. Nominally these errors range from 5 to 25 m (Lachapelle, 1991), but have been degraded to as much as 100 m (Kremer et al., 1989) through selective availability. Satellite clock errors are about 10 m assuming clock corrections made available in the satellite message are used (Wells et al., 1986).

All discussions up to this point have assumed GPS signals travel at the speed of light. Two sections of the atmosphere defy this assumption: the layer of free electrons ranging from about 50 to 1000 km above the earth referred to as the *ionosphere*, and the layer up to 80 km above the earth referred to as the *troposphere* (Wells et al., 1986). *Ionospheric errors* range from 50 m at zenith (i.e. when the elevation angle is 90) to 150 m at the horizon (i.e. when the elevation angle is 0). *Tropospheric errors* range from 2 m at zenith to about 20 m at 10 elevation (Wells et al., 1986). The errors for satellites at low elevation angles are greater because they have longer paths through the troposphere and ionosphere.

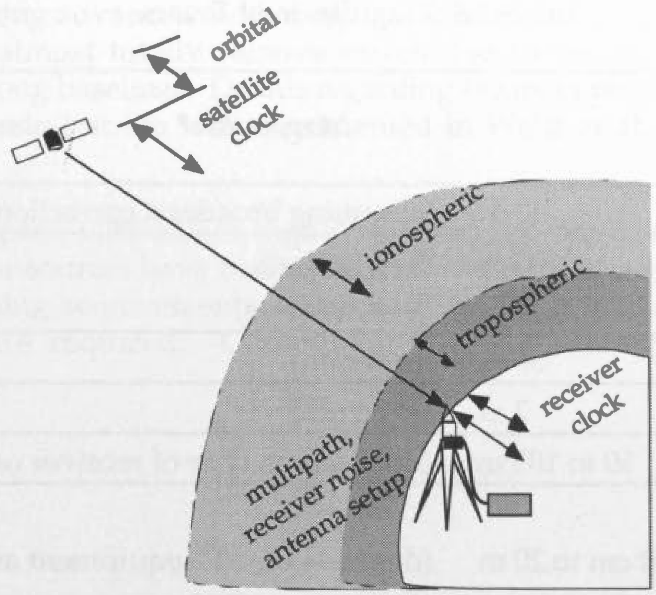


Figure 2.17 Common Errors

Receiver clock errors may range from 10 m to 100 m depending on the quality of the receiver clock (Wells et al., 1986). In positioning, this clock error is estimated along with coordinates and so does not greatly affect achievable accuracies.

Multipath errors occur when signals received directly, combine with signals reflected off nearby objects such that the true signal is corrupted by interference from the reflected signal. *Receiver noise* is a function of how well a GPS receiver can measure code or carrier observations. The magnitude of both multipath and receiver noise errors is proportional to the chip length and wavelength of the code and carrier measurements respectively. For C/A code measurements, multipath can be as high as 20 m (Lachapelle et al., 1989) whereas for L1 carrier it can never exceed 5 cm (Georgiadou and Kleuseberg, 1988). Receiver noise for code and carrier measurements are typically at the few metre and few millimetre levels respectively. Both receiver and antenna design may influence multipath and measurement noise (Van Dierendonck et al., 1992).

The magnitude of errors as they affect a single satellite-receiver range are summarized in Table 2.4. All the errors presented in Table 2.4, when combined using scientific laws of error propagation, form the *user equivalent range error*. It is this value, which when multiplied by the DOP (dilution of precision), yields an estimate of achievable accuracies for single point positioning.

Table 2.4 Magnitude of Errors

Error	Magnitude*	
satellite clock	10 m	(assuming broadcast corrections used)
orbital	100 m	(S/A active)
	5 to 25 m	(S/A inactive)
ionospheric	50 m	(at zenith)
tropospheric	2 m	(at zenith)
receiver clock	10 to 100 m	(depends on type of receiver oscillator)
multipath		
C/A code	50 cm to 20 m	(depends on GPS equipment and site)
carrier	up to a few cm	(depends on GPS equipment and site)
receiver noise		
C/A code	10 cm to 2-3 m	(depends on receiver type)
carrier	0.5 - 5 mm	(depends on receiver type)

* references for error magnitudes given in text

An error unique to carrier phase observations is the *cycle slip*. Recall from the discussion preceding the carrier equation (2.2), that carrier phase is measured continuously, but has an ambiguity term at the time of initial satellite lock. The failure to maintain continuous lock on a satellite causes cycle slips, in which an integer number of wavelengths may be lost. Cycle slips must be corrected through data processing if carrier measurements are to be used to achieve sub-decimetre accuracy.

The wide range of accuracies and positioning techniques with GPS are a result of the type of observations used (code, carrier or both) and the means for handling the errors listed in Table 2.4. When accuracies better than the 100 m 2drms achievable with single point positioning are required, relative positioning should be employed. In relative positioning most of the orbital, tropospheric and ionospheric errors along the satellite-receiver path are common to both sites and consequently their influence on the relative positions is small. The closer the GPS receivers are to each other, the more common are these errors and the greater the accuracy achieved through relative positioning. Accordingly, the further apart the GPS receivers are from each other, the less common are these errors and the less accurate the relative positioning.

For precise static relative positioning, sophisticated means for handling errors are employed which include combining observations through double differencing techniques and using advanced modelling and estimation. Dual frequency receivers may be used to almost totally remove errors due to the ionosphere in relative positioning over long baselines. Details regarding errors in precise static surveys are not presented herein but are well documented in Wells et al. (1986) and Cannon (1991).

In this chapter, GPS basics, signal components, positioning types, satellite visibility and error sources have been reviewed. Before discussing how to use GPS to fulfill positioning requirements, some basic concepts of locating data on the earth's surface are required. Consequently, the following chapter discusses positioning basics.

CHAPTER 3
POSITIONING - BASIC CONCEPTS

In this chapter, positioning concepts which are important in the application of the Global Positioning System are described. These include measures of accuracy, heights and the geoid, and coordinate systems and datums. It is especially important to understand the difference between heights determined with GPS and heights determined with traditional levelling techniques (discussed in Section 3.2).

3.1 MEASURES OF ACCURACY

When carrying out any measurement it is important to quantify its "goodness". For instance, if a position was to be determined with GPS, one would want to know with a quantifiable degree of certainty, if this position would be accurate to 100 m or 10 cm. It is also important to be aware of the various terms used to quantify measurement accuracies and the relationship between them so that GPS accuracy claims may be compared. The objective of this section is to explain the basic terms associated with measures of accuracy.

Accuracy and Precision

The terms accuracy and precision are worthy of clarification. *Accuracy* refers to how close an estimate (or measurement) is to the true but unknown value, while *precision* refers to how close an estimate is to the mean estimate. It is possible to have high accuracy with low precision and vice versa as shown in Figure 3.1. In the figure, the centre of the circles represent the "correct" position and each dot represents an individual estimate.

Errors which limit the accuracy of any measurement may be classified as gross, systematic or random. *Gross errors* (also referred to as *blunders*) are errors which result from some equipment malfunction or observer's mistake. For example, if an operator of a GPS receiver recorded the height of an antenna above a monument as 0.5 m instead of a correct height of 1.5 m a gross error is said to have occurred. Gross errors must be detected and corrected. *Systematic errors* are those which have some known pattern or behavior which biases the observations. Ideally systematic errors are removed from observations by modelling. For example, much of the error due to the tropospheric delay referred to in Section 2.5 may be removed by applying a mathematical model which represents tropospheric behaviour. If all gross and systematic errors are removed from observations, only *random errors* remain. Precision (Figure 3.1) includes only random effects, while accuracy includes both random and systematic effects (Mikhail, 1976).

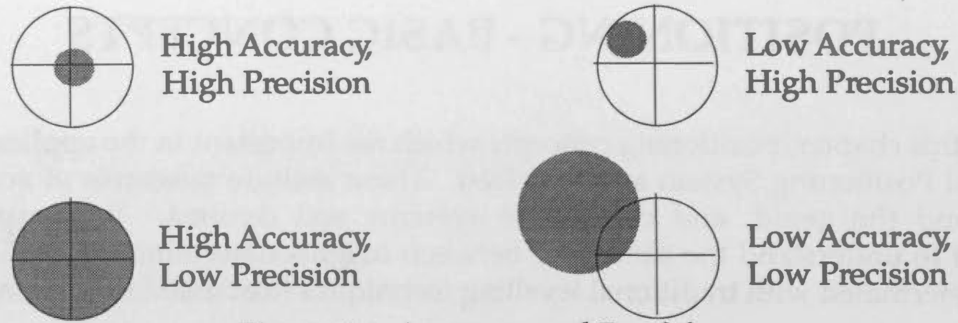


Figure 3.1 Accuracy and Precision

Random errors have the property that if enough observations are made there will be equal probability of negative and positive errors, yielding a mean value of zero. Random errors, according to statistical theory, tend to be distributed about the mean following the normal probability distribution function (Figure 3.2). The area under the curve represents all potential random error outcomes according to the theory of normal distribution.

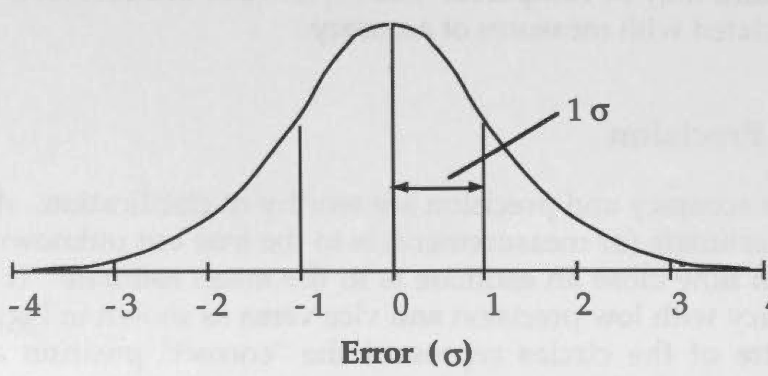


Figure 3.2 Normal Probability Distribution Function

The *standard deviation*, represented by the symbol σ, is used to quantify dispersion about the mean and is shown on the normal probability distribution function (Figure 3.2). The certainty of a solution may be quantified by multiples of the standard deviation or by probability. The normal probability distribution function gives the relationship between the two. For example, a standard deviation of 1σ is associated with a probability of 68.3% (the percent of the area under the curve in Figure 3.2 bounded by 1) and a 95% probability is associated with 1.96σ

(Mikhail, 1976). Further relationships between standard deviations and probability are summarized in Table 3.1.

Table 3.1 Relationship Between Standard Deviation and Probability - 1D Case*

Multiples of σ	Probability
1 σ	68.27%
2 σ	95.45%
3 σ	99.73%

Probability	Multiples of σ
90%	1.645 σ
95%	1.960 σ
99%	2.576 σ

*Mikhail (1976)

Standard deviation is the most common accuracy measure used in positioning. It may be approximated experimentally by taking a large number N, of measurements x, summing the square of the difference of each measurement from the mean $\bar{x}$, dividing by the total number of measurements minus one, and then taking the square root, as shown in equation (3.1).

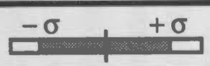
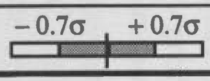
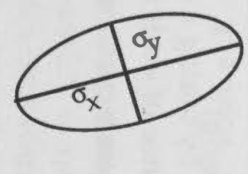
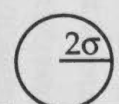
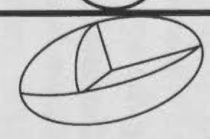
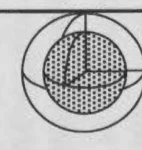
$$\sigma_x = \sqrt{\left(\sum_{n=1}^{N} (x_n - \bar{x})^2\right) / (N-1)} \tag{3.1}$$

The value computed using equation (3.1) is referred to as the *root mean square* (rms). Although rms and σ have slightly different definitions in a statistical sense, they are often used interchangeably as will be done herein. Related terms include the mean square error (MSE), which is the square of equation (3.1), i.e. σ_x^2.

Another term less commonly used to quantify measurement accuracy is *probable error*, which indicates 50% uncertainty and corresponds with 0.674σ (National Geodetic Survey, 1986). Note that standard deviation, rms and probable error are all one dimensional measures of accuracy, yet with GPS, two and three-dimensional accuracy measures are also important.

Measures of accuracy commonly used with GPS for one, two and three-dimensional cases are shown in Table 3.2. In the table, the first column indicates

Table 3.2 Common Accuracy Measures Used With GPS

(1)	(2)	(3)	(4) **Prob.**	(5) **Approximation**	(6) **Sketch**	(7) **Related Expressions**
1D	rms	root mean square	68.3%*	σ		MSE - mean square error (the square of the rms)
	PE	probable error	50%*	$0.674\ \sigma$**		
2D		error ellipse	39.4%*	defined by σ_x, σ_y & correlation		
	CEP	circular error probable	50%*	radius: $0.589\ (\sigma_x + \sigma_y)$*		CEP - also called CPE (circular probable error)
	2drms	twice distance root mean square	varies 95.4 - 98.2%†	radius: 2σ† $\sigma = \sqrt{\sigma_x^2 + \sigma_y^2}$		2nd less common definition: 2 dimensional rms (circle's radius 1σ)
3D		error ellipsoid	19.9%*	defined by σ_x, σ_y, σ_z & correlations		
	SEP	spherical error probable	50%*	radius: $0.513(\sigma_x+\sigma_y+\sigma_z)$*		SEP - also called SPE (spherical probable error)

*(Mikhail, 1976) †(Langley, 1991) **(National Geodetic Survey, 1986)

the dimension, the second the acronym (if applicable), the third, the name, the fourth, the associated probability level, the fifth, the relationship with standard deviation, the sixth, a pictorial representation, and the seventh, related expressions and definitions.

Note for the two and three-dimensional cases, an error ellipse and error ellipsoid are included in the table. These accuracy measures account for the probability of errors varying with direction. Error ellipses are defined by the standard deviations of the coordinates and their correlations. The correlations, which describe the effect an error in one component has on the other, result in ellipsoid axes being oriented in directions which differ from the coordinate axes. Although in the figure errors are given in terms of x and y, the same concept applies equally to latitude and longitude. Error ellipsoids follow the principle of error ellipses, but are extended to three-dimensional space.

The other terms shown in Table 3.2 which represent accuracy measures for two and three-dimensional space are defined by single values which represent radii rather than more complex ellipses and ellipsoids. The circular error probable (CEP) and spherical error probable (SEP) both represent 50% probability for circles and spheres respectively. The approximate relationships of their radii with the more rigorously defined error ellipse and ellipsoid are given in column (5) of Table 3.2.

One last measure of accuracy commonly used in two dimensional space with GPS is 2drms. It is defined as the circle with radius 2σ, where σ is the standard deviation of a vector in two dimensional space. The probability level for 2drms varies from about 95.4 to 98.2% depending on the relative magnitudes of σ_x and σ_y (Langley, 1991).

Absolute and Relative Accuracy

Similar to absolute (single point) and relative GPS positioning, as described in Section 2.3, accuracy measures may also be considered as absolute or relative. *Absolute accuracies* are estimates of how close a position is to the truth in the earth's reference frame, and *relative accuracies* are estimates of how well a vector between two points is measured (e.g. the accuracy of a distance measurement between two points).

Absolute accuracies are always represented as constant values. For example, horizontal positions determined by GPS single point positioning, assuming favourable satellite geometry, are accurate to 100 m at 2drms horizontally and 156 m at 2σ vertically (U.S. DoD and DoT, 1986). *Relative accuracies* may be represented as constant values, as parts per million (ppm), or both. Parts per million are used to relate error magnitudes with *baseline* length. For example 1 ppm corresponds to a 1 mm error over 1 km and a 1 cm error over 10 km. The linear relationship between errors and baseline distance for 2, 10 and 20 ppm is shown in Figure 3.3a.

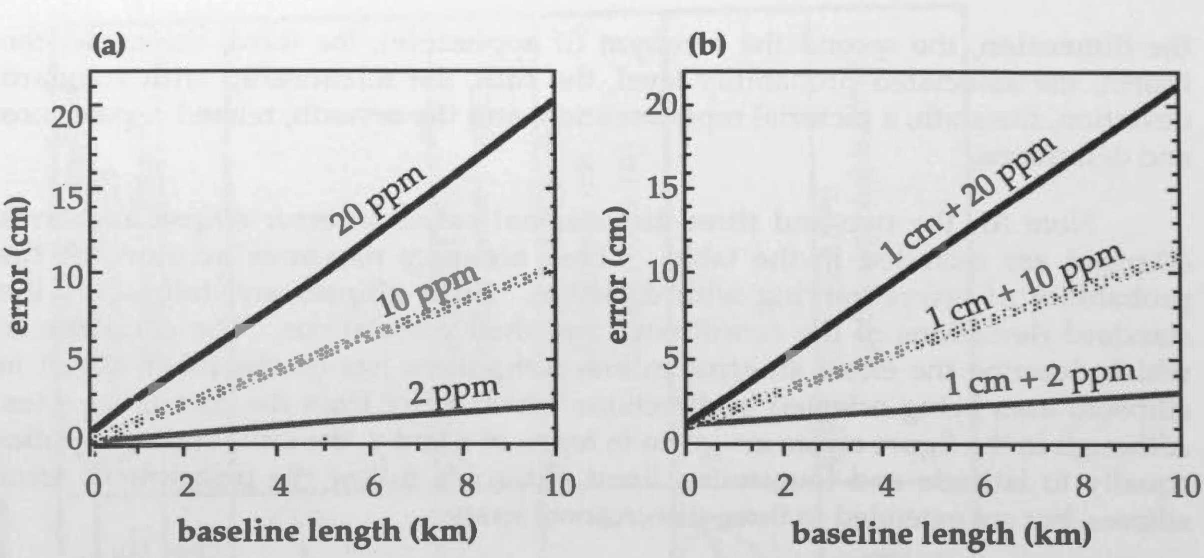


Figure 3.3 GPS Relative Accuracies - PPM a) ppm b) constant + ppm

Baseline accuracies using GPS are often expressed combining a constant term (e.g. 1 cm) with a linear term (e.g. 1 ppm). For example, the accuracy of a precise survey could be specified as:

$$\text{rms accuracy} = 1 \text{ cm} + 1 \text{ ppm}. \qquad (3.2)$$

The same relationship shown for ppm in Figure 3.3a is shown in 3.3b with the addition of a 1 cm constant. In GPS, the constant term accounts for errors which are independent of baseline length such as antenna set-up and multipath errors, while the linear term accounts for length dependent errors such as residual orbital, tropospheric and ionospheric errors.

Comparing Figures 3.3a and 3.3b, it can be seen that the 1 cm constant, when applied to the 2 ppm case contributed to a 50% increase in error magnitude over 10 km, but was almost insignificant for the 10 and 20 ppm cases. It is for this reason, blended accuracy measures as shown in equation (3.2) are usually only used with precise relative surveys.

Accuracy, precision, standard deviation, rms, CEP, SEP, 2drms and ppm are terms anyone using GPS or reviewing GPS literature is apt to encounter. The above explanations of these terms should therefore be of value for application oriented users. All discussions of accuracies throughout the remainder of these guidelines are based on these terms.

Other aspects essential to positioning on earth are an understanding of the relationship between measurements on the earth's surface, measurements made using GPS satellites orbiting the earth, and the relationship between the two.

Discussion of these subjects will be dealt with in the following two sections, the first dealing with height systems, and the second dealing with coordinate systems.

3.2 HEIGHTS AND THE GEOID

Heights and height differences may be determined using GPS, but with lower accuracies and higher complexities than the corresponding horizontal components. The main difficulty in determining heights lies with the GPS satellite's dependence on ellipsoidal heights and most user's requirement for orthometric heights. It is therefore very important that those interested in applying GPS for height determinations understand the differences between these height systems and how to deal with them. This section provides introductory background information towards this end.

Orthometric and Ellipsoidal Heights

Heights are traditionally determined using levelling techniques which are based on the earth's gravity field and referenced to mean sea level. At each point on the earth, gravity has a certain magnitude and direction which can be described by a vector. Every time an instrument is levelled, the line of sight is set perpendicular to the gravity vector at that point, and every time a levelling rod is held on a point, it is held in line with the gravity vector. The heights determined through levelling are usually referred to as elevations above mean sea level. These elevations are called *orthometric heights* and actually are referenced to the *geoid*. Orthometric heights are the heights (or elevations) which see everyday use and are found on topographical maps.

The *geoid* is the equipotential surface (i.e. the surface on which the gravity potential is constant) which best approximates mean sea level. It forms a smooth but irregular surface around the earth. Mathematically, it is a very complex surface to represent. On the other hand, the *ellipsoid*, which is in essence a squashed sphere, is easily represented and manipulated mathematically. It is for this reason that an ellipsoid is used to approximate the geoid, and that ellipsoidal heights based on the ellipsoid are determined rather than geoid heights based on the geoid. Elevations determined using GPS satellites are based on the ellipsoidal surface. The relationship between the ellipsoid and geoid is illustrated in Figure 3.4.

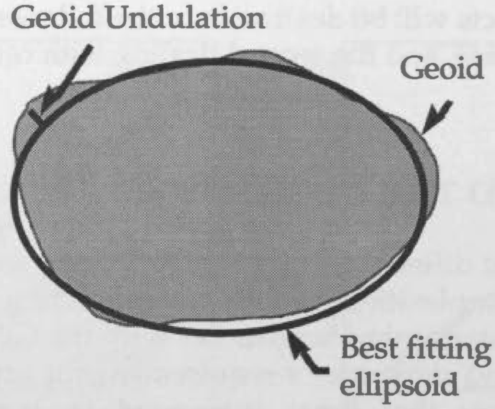


Figure 3.4 Geoid and Ellipsoid

The distance separating the geoid and the ellipsoid is the *geoid undulation* (also called geoid height). The geoid undulation may be positive or negative depending on whether the geoid is above or below the ellipsoid at a given point (Figure 3.4). If the geoid undulation, N, and the ellipsoidal height, h, are known, the orthometric height may be determined using the relationship illustrated in Figure 3.5. That is, the orthometric height is equal to the ellipsoidal height minus the geoid undulation.

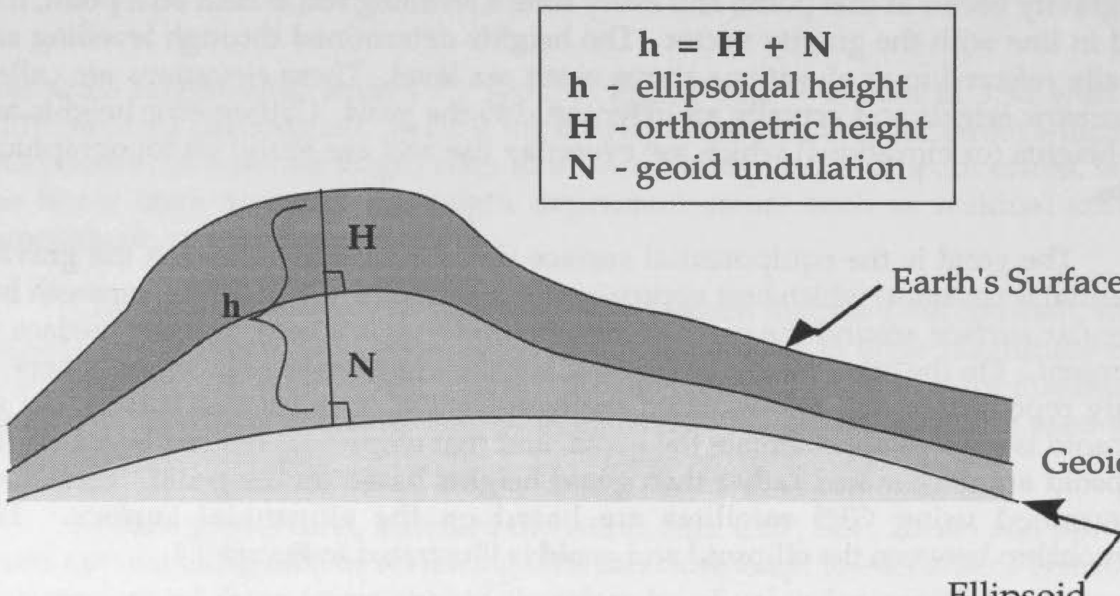


Figure 3.5 Relationship Between Orthometric and Ellipsoidal Heights

It is evident that one must know geoid undulations to compute orthometric heights with GPS.

Geoid Models

Geoid undulations vary by as much as 100 m over the earth's surface and by 50 m over Canada. *Geoid models*, which describe the pattern of geoid undulations over the earth, provide the link between orthometric and ellipsoidal heights. Numerous geoid models have been produced by geodesists by combining scientific theory and various types of gravity measurements. With a geoid model, given a specific latitude and longitude, one can look up or interpolate the geoid undulation.

Geoid models have varying levels of accuracy and areas of coverage. In general, the more accurate the geoid model, the more computationally intensive it is to produce, and the more storage space required. Some geoid models are available for the whole world, and some only for specific regions. For example, the Geodetic Survey Division of EMR has computed a geoid, GSD91, which covers only Canada, but has a level of accuracy and detail which exceeds any available global geoid models and is one of the most accurate models available for Canada. It is available from the Geodetic Survey Division (GSD), in disk format, along with software to interpolate geoid undulations for specific locations in Canada. GSD also provides geoid information for other parts of the world to support Canadians working abroad. (See Appendix E for further information.)

Many GPS receivers, GPS software, or both have "built-in" geoid models. That is, they have the means to correct for the geoid - ellipsoid separation at any given position determined with GPS. These models are usually low accuracy models which apply to the full earth's surface, and have rms' of about 1.0 m. With low accuracy hand held GPS receivers, the conversion from ellipsoid to orthometric heights may even be made transparent to the user.

The need for and accuracy level required of geoid models depends on whether single point or relative positioning is used (Table 3.3). For single point positioning (Figure 2.7), a geoid model must always be used if orthometric heights are sought. However, since single point positioning is only accurate to 100 m 2drms horizontally and 156 m 2σ vertically (U.S. DoD and DoT, 1986), the effect of geoid undulation inaccuracies at the 1.0 m rms level is negligible.

Table 3.3 Geoid Model Requirements For Point and Relative Positioning

GPS Positioning Type	Use Model?	Need High Accuracy?	Why?
single point	yes	no	must correct for geoid to attain orthometric height single point positioning accuracy low, so high accuracy geoid is of no benefit
relative	yes	varies	depends on baseline lengths, geoid gradient and desired accuracy

For relative positioning, the situation is very different. Recall from Figure 2.8, that relative positioning always involves determining an unknown point relative to a known point. Hence it is not only the absolute geoid undulation that is of concern, but also the difference between the geoid undulations at the known and unknown points. The use of a geoid model is more complex and variable depending of the accuracy level required, and is accordingly left for Section 5.4 which discusses procedures to determine relative heights using GPS.

Up to this point two different surfaces with respect to heights have been discussed: the geoid and the ellipsoid. The ellipsoid is also the basis for all horizontal measurements made using GPS and Canada's national framework of control points. This brings us to discussion of coordinate systems, datums and control networks as they relate to GPS.

3.3 COORDINATE SYSTEMS AND DATUMS

It is important to understand the reference systems upon which horizontal and vertical coordinates are based and how they relate to GPS coordinate systems.

Coordinate Systems

Although not explicitly stated, two types of coordinate systems have been referred to in these guidelines: the conventional terrestrial system and the geodetic coordinate system.

The *conventional terrestrial coordinate system* has its origin at the centre of the earth, its Z axis directed towards the north pole, its X axis passing through the plane which contains the Greenwich Meridian, and its Y axis perpendicular to the X and Z axes to form a right handed system. The positive axes of the conventional terrestrial system are shown in Figure 3.6. Conventional terrestrial coordinates are convenient to work with mathematically as was seen with the single point positioning equation (2.5). However, for many applications they are not as suitable as coordinate systems with more physical significance on the earth, such as the geodetic coordinate system.

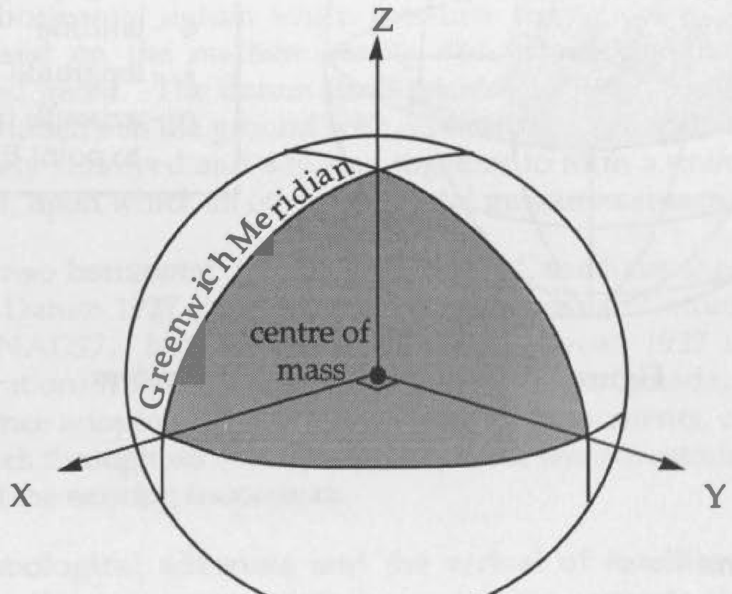


Figure 3.6 Conventional Terrestrial System

Geodetic coordinates include the familiar latitude, longitude and height components and are all based on the ellipsoid. Latitude is the positive angle from the centre of the earth northwards from the equator, longitude is the positive angle eastwards from the Greenwich Meridian, and the ellipsoidal height is the height above the ellipsoid's surface as mentioned previously. Latitude and longitude for the point "Origin" are shown in Figure 3.7. (In the figure longitude is negative.) The azimuth from the "Origin" to a second point "B" is also shown.

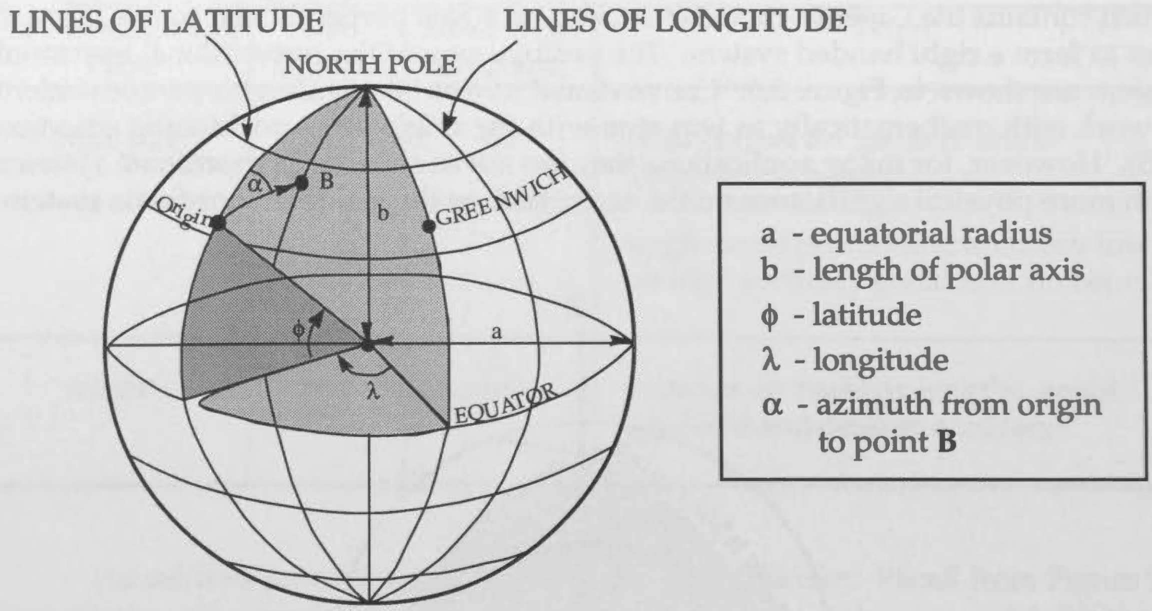


Figure 3.7 Geodetic Coordinate System

Vertical Datums

So far, coordinate systems and the difference between orthometric and ellipsoidal heights have been discussed, but the datums upon which these systems are based for real applications have yet to be addressed. *Datums* can be defined as surfaces or sets of quantities upon which measurements are based. Two different types of datums must be considered: vertical datums and horizontal datums.

In Canada, elevations above mean sea level are based on the Canadian Geodetic Datum 1928 (CGD28). The datum was derived from mean sea level as determined at Halifax, Yarmouth and Pointe-au-Pere in eastern Canada, and Vancouver and Prince Rupert on the west coast (Young and Murakami, 1989). A network of approximately 70,000 bench marks (monuments in the ground with accurate elevations) established through spirit levelling is currently maintained by the Geodetic Survey Division. Orthometric heights for any of these bench marks may be obtained from the Geodetic Survey Division. (See Appendix D.) In Canada, bench mark elevations and topographical map elevations are almost all based on the same datum. Provincial agencies and many municipal agencies also maintain networks of bench marks, with the former usually being of second order accuracy, and the latter of third order accuracy. Details on orders of accuracy for control surveys are given in "Specifications and Recommendations for Control Surveys and Survey Markers" (Surveys and Mapping Branch, 1978).

In Canada, to facilitate data exchange, elevations should be referenced to the national vertical datum. For projects in other countries, if a well established system of bench marks based on a common reference datum is available, it should be used and the reference datum upon which elevations are based should be clearly specified.

Horizontal Datums and NAD83

Canada's horizontal datum which provides the reference for latitude and longitude, is based on the mathematically defined ellipsoid rather than the physically defined geoid. The datum itself consists of a large number of survey markers (i.e. monuments in the ground with accurate latitude and longitude) which have been precisely surveyed and adjusted together to form a uniform network of horizontal control, upon which all other horizontal measurements may be based.

There are two horizontal datums with which Canadians should be familiar: North American Datum 1927 (NAD27) and North American Datum 1983 (NAD83) which replaces NAD27. NAD27 was computed between 1927 and 1932 using surveying observations from networks of monuments from Canada, Mexico and the United States. Once adopted, all new survey control monuments, connected to the existing framework through surveying measurements, were constrained to fit within or extend beyond the existing framework.

With technological advances and the arrival of satellite surveying, the measurements to the new monuments became more accurate than the NAD27 datum and were degraded through integration with NAD27. It was recognized by national geodetic agencies of Canada, Mexico and the United States, that a recomputation was needed, as the adopted NAD27 coordinates were not accurate enough to satisfy modern requirements. As a result, a project to define a new datum and readjust the North American positional control survey networks was undertaken, culminating with the official adoption of NAD83 in 1990.

Shifts in geodetic coordinates resulting from the transition from NAD27 to NAD83 range from about 120 metres westerly on the west coast to 70 metres easterly in Newfoundland and 100 metres northerly in the high Arctic. The corresponding Universal Transverse Mercator (UTM) coordinates have a fairly consistent northward shift ranging from about 200 to 250 metres (Pinch, 1990). The shifts are a result of distortions in the NAD27 coordinates which were removed in the readjustment, and the use of an ellipsoid which better fits the shape of the earth.

One key benefit of NAD83, is that it is consistent with the reference frame upon which GPS satellites are based. That is to say, with single point positioning, the coordinates a receiver will output will be NAD83 coordinates. If one required the use of another datum, for example NAD27, a transformation between the two coordinate systems would be required.

Coordinates for survey control monuments, maps, databases and Geographical Information Systems (GIS) are affected by the new datum. The conversion of geodetic survey control and map products maintained by EMR from NAD27 to NAD83 coordinates is well underway. Table 3.4 summarizes some of the EMR policies regarding NAD83. (See SMRSS (1990) for further details.)

Table 3.4 Conversion to NAD83

	Policies* and Status
National Control Network	NAD83 was officially adopted by EMR in 1990 NAD83 coordinates have been computed for about 105,000 survey control points in Canada GSD provides access to and advice on means to transform coordinates from NAD27 to NAD83 GSD will support the development of transformations from other major geodetic reference systems used in Canada to NAD83
EMR Map Products	NAD83 will be the official datum for all graphical and digital products existing products will be converted to NAD83 on a continuing long-term basis as an interim measure, margin notes which enable conversion to NAD83 coordinates will be over-printed on existing maps CCM will publish information explaining the conversion and listing of UTM shifts for each of the 1:50,000 and 1:250,000 maps of the NTS series.

* SMRSS(1990)

The implications of NAD83 for those interested in geographically referenced information are plentiful. Foremost, it is recommended that databases and GIS' be referenced to NAD83. The new datum has the benefits of being free of the major distortions which plague NAD27 and is directly compatible with GPS determined positions. Furthermore, as the decade proceeds, more and more fundamental geographical data will be referenced with NAD83 coordinates, including the National Topographical Map Series.

As mentioned, the GPS reference system is compatible with NAD83. Consequently, in relative positioning, "known" points should always be given in NAD83 coordinates. If coordinates are later needed in a different reference system, transformations may be carried out after solving for the GPS NAD83 coordinates. Table 3.5 summarizes considerations in database or GIS management and GPS positioning as a result of NAD83.

Table 3.5 The Influence of NAD83 on Locational Parameters

Task	Influence of NAD83
Database or GIS Management	datum used should be clearly specified adoption of NAD83 recommended should have ability to convert from any other commonly used datum to NAD83
Single Point Positioning with GPS	computed coordinates will be NAD83 compatible transformation of coordinates to another datum may be carried out using receiver software or other acceptable transformation
Relative Positioning with GPS	NAD83 coordinates should be used for the "known" point

Traditionally, horizontal and vertical control networks have existed separately because they have been dependent on different surveying techniques. With GPS, horizontal and vertical coordinates are simultaneously determined and interdependent, although the computed heights will always be the ellipsoidal height, unless corrected for the geoid undulation. Accordingly, "known" points for relative positioning should be known both horizontally and vertically. This is discussed in more detail with procedures in Section 5.1.

The basic concepts of accuracy, the geoid and datums, presented in this chapter are apt to be encountered by anyone who knowledgeably uses GPS to fulfill specific positioning requirements. The following chapter uses the fundamentals of GPS and positioning to explain the various positioning methods possible with GPS.

CHAPTER 4

GPS POSITIONING TECHNIQUES

The objective of this chapter is to give those interested in applying GPS, a general familiarity with the wide variety of techniques which presently exist, and their respective accuracies, level of complexities and costs. This information provides a starting point from which the best technique for a given application may be assessed.

The information in this chapter is limited in two ways. First, the accuracies reported only give general ideas of accuracy levels which may be expected using a given technique. Many variables affect these accuracies, such as baseline lengths, ionospheric conditions, the magnitude of selective availability, receiver types used and processing strategies adopted. Second, although techniques currently available are described, with the rapid pace of advancements in GPS technology other techniques may soon become available. Nevertheless, with the background on GPS and positioning from Chapters 1 and 2, and the presentation of current techniques in this chapter, one should be able to readily evaluate new techniques as they become available.

GPS positioning techniques may be categorized as being predominantly based on code or carrier measurements. Code techniques are generally simple and produce low accuracies, while carrier techniques are more complex and produce higher accuracies (Table 2.2). For both code and carrier measurements, a variety of positioning methods exist. The suitability of each for a specific application is dependent on the desired accuracies, logistical constraints and costs.

Representative accuracies and levels of complexity for the various methods are presented in Table 4.1 for code techniques and in Table 4.2 for carrier techniques. Each table lists methods, the basic underlying concepts, the minimum number of receivers required (Min. # Rcvrs), the observation period required (Obs. Time), the accuracy, and comments. For Table 4.1 accuracies are shown at the 95% probability level, while for Table 4.2 rms accuracies are shown. Please note that vertical accuracies pertain to ellipsoidal rather than orthometric heights. If orthometric heights are desired, one must also account for variations in the geoid as discussed in Sections 3.2 and 5.4. The GPS positioning methods listed in Tables 4.1 and 4.2 are described in Sections 4.1 and 4.2 respectively.

Table 4.1 Summary of Code GPS Positioning Methods*

Method	Basic Concepts	Min. # Rcvrs	Obs. Time	Accuracy (at 95% prob.)	Comments
Single Point (static or kinematic)	need at least four satellites instantaneous position	1	1-10 s	100 m horizontally 156 m vertically	simplest, lowest cost
Differential (static or kinematic)	need at least four satellites apply corrections measured at monitor receiver to rover receiver	2	1-50 s	3 to 12 m† horizontally and vertically	simple, low cost

* assuming C/A code used † (Lachapelle et al., 1991)

4.1 CODE POSITIONING TECHNIQUES

Code techniques may be grouped as single point or differential positioning (Table 4.1). Only C/A code observations are considered for the code techniques because P code is scheduled to be unavailable for civilian use by the end of 1993, when the full GPS constellation is operational (McNeff, 1991).

Single Point Positioning

Single point positioning (Figure 2.7) is achieved by intersecting the measurements from four or more satellites at a single receiver on the earth's surface. (See Section 2.3 for details.) The accuracies achievable using single point positioning are 100 m 2drms horizontally and 156 m 2σ vertically (U.S. DoD and DoT, 1986), assuming favourable geometry (e.g. PDOP < 6). These accuracies apply equally to static or kinematic single point positioning. Solutions may be attained almost instantaneously, using an inexpensive hand-held GPS receiver. The receiver need only collect C/A code measurements to achieve the specified single point positioning accuracy.

Table 4.2 Summary of Carrier GPS Positioning Methods

Method	Basic Concepts	Min. # Rcvrs	Obs. Time	Accuracy (3D rms)	Comments
Static	simultaneous site occupation	2	1 h	1 cm + 1 ppm to 10 ppm	complexity varies
Kinematic (carrier based)	moving rover positioned with respect to static monitor, need initial ambiguity resolution	2	–	10 cm to 1 m	logistically difficult since must maintain lock while moving
Semi-Kinematic (also called Stop & Go)	rover stopped temporarily on points to be positioned with respect to monitor	2	~1 min. per point	a few cm	limited to baselines under ~10 km, must maintain lock while moving between points
Pseudo-Kinematic	each rover site occupied twice, at least one hour apart, to exploit change in satellite geometry	2	1-3 min.	a few ppm	double site occupation essential, logistically cumbersome
Rapid Static	uses sophisticated techniques and extra information to resolve ambiguities	2	3 to 5 min.	a few cm	generally for baselines under 10 km, need "extra" measurements

Note: All vertical accuracies refer to ellipsoidal heights.

The successful application of single point positioning requires a receiver to track at least four satellites (preferably more) with good geometry, and the ability to manage the wealth of positional information which may be collected in a short time period. Real-time position determination with single point positioning is a standard feature on most GPS receivers. This however does not preclude the potential need for downloading data from a receiver to a computer for data management or database integration (Figure 2.10c).

Errors which affect single point positioning may be significantly reduced through *relative positioning*. The most simple form of relative positioning is achieved by applying corrections to the code measurements sensed at a "known" *monitor* site, to the measurements at an "unknown" *rover* site. This type of positioning is referred to as *differential positioning.*

Differential Positioning

Differential positioning may be conducted with either post-mission or real-time processing. The former is simpler and less expensive, while the latter is complicated by the requirement for a data link. Differential corrections may take the form of measurement corrections or position corrections. Although the former is the more rigorous recommended approach, the concepts behind both correction forms are explained. With either approach, the coordinates of one point which is used as a *monitor* station, must be "known".

With the *measurement method*, the "true" range, ρ, between a satellite and monitor station is computed as

$$\rho^{s}_{rk} = \sqrt{(x^s - x_{rk})^2 + (y^s - y_{rk})^2 + (z^s - z_{rk})^2}, \tag{4.1}$$

where (x^s, y^s, z^s) are "known" satellite coordinates derived from the *broadcast ephemerides* and (x_{rk}, y_{rk}, z_{rk}) are "known" receiver coordinates. (Note, equation (4.1) is analogous to equation (2.5).) The errors for the satellite-receiver range are computed by rearranging equation (2.4), as

$$\text{errors} = P^{s}_{rk} - \rho^{s}_{rk} \tag{4.2}$$

where P^{s}_{rk} is the observed satellite-receiver range and ρ^{s}_{rk} is the "true" satellite-receiver range. Because the major errors which affect GPS observations (orbital and atmospheric) will affect points near the monitor station by approximately the same magnitude, equation (4.1) may be used to correct observations made at nearby sites. The errors computed at the monitor site thereby form differential corrections which are applied at the *rover* site (also called *remote* site). This is the basic concept of differential positioning using the measurement method.

With the *position method*, the "true" monitor receiver position (x_{rk}, y_{rk}, z_{rk}) is compared to the position computed through single point positioning (x_r, y_r, z_r). The resulting positional errors (i.e. the differences $x_r - x_{rk}$, $y_r - y_{rk}$, $z_r - z_{rk}$) at the monitor site form differential corrections which are applied at the rover site. With this method, exactly the same satellites must be used at both the monitor and rover sites. This is a limitation since obstructions of a satellite at one site may prevent its successful application. The measurement method is preferred over the position method for differential positioning.

The further a monitor site is from a rover site, the more the errors at the two sites will differ and the less accurate the position determination using differential techniques will be. For example, Lachapelle et al. (1991) report horizontal and vertical accuracies using kinematic code differential techniques over 50 km at 4-9 m horizontally and 5-11 m vertically (at 95% probability with PDOP < 3.0), and over 500 km at 6-11 m and 7-12 m for the same components.

To apply differential positioning with *post-mission processing*, one receiver is positioned on a "known" point, while a second is moved to each point to be positioned. After completion of data collection, the data is combined together on a computer for post-processing (Figure 2.10d). One of the very important parts of the post-processing algorithms is to match the exact time of the observations at the monitor receiver with the identical times for observations at the rover receiver, so that the proper differential corrections are computed and applied. Another major part of differential positioning is data management. Potentially hundreds of points may be positioned in a day. A means to tag and integrate this data within a database is essential.

As previously mentioned, to apply differential positioning with *real-time processing*, a data link is required to transmit data from the monitor site to the rover site (Figure 2.10b). One drawback of real≅time differential processing is the time delay between when a GPS measurement is made at the monitor site, and the time it takes to send and implement the correction at the rover site. The time delay may degrade accuracy slightly over what is possible in post-mission processing. Although it is expected that real-time differential positioning will become more plausible in the next few years with the rapid pace of GPS related technological developments, at present, the simplicity and lower cost incurred with post-processing techniques makes the latter more appropriate for many applications.

4.2 CARRIER POSITIONING TECHNIQUES

Several techniques for using carrier phase observations for GPS have been developed over the past decade. These include static, kinematic, semi-kinematic, pseudo-kinematic and rapid static techniques.

Before delving into the carrier techniques summarized in Table 4.2, it is necessary to review some elements of the use of carrier observations. Recall from the discussion in Section 2.2 that much higher accuracies may be achieved using carrier observations than using code observations. However carrier observations are complicated by the unknown number of cycles (ambiguities) when a satellite is first tracked (equation (2.2)). The variety of techniques which may be used with carrier measurements are based on the ways in which these ambiguities are handled.

Note that all carrier GPS positioning methods shown in Table 4.2 are relative rather than single point (i.e. they need at least two receivers). Since the errors in single point positioning far exceed the code measurement accuracy itself, there is no benefit in using the more accurate but more complex carrier observations for point positioning.

In relative positioning using carrier observations, the ambiguities for each satellite are estimated along with the coordinates of the unknown station relative to the known station. Theoretically these ambiguities should be integer numbers because they physically represent the whole number of cycles between the satellite and receiver when a satellite is first locked on. However, due to errors, the estimated ambiguities usually are not integers. The larger the errors present in the data (e.g. due to relative differences of the ionosphere over long distances) the farther from integers the estimated ambiguities are apt to be.

Over short baselines (say 10 to 15 km) it may be possible to decide what integer ambiguities are correct, hold these ambiguities constant, and solve for only the (x,y,z) coordinates of the unknown point. In such cases when ambiguities can be fixed to the correct integer, much higher accuracies may be achieved. It is for this reason that all the methods listed in Table 4.2 are designed with the goal of optimizing the potential for having ambiguities fixed to the correct integer. The five methods mentioned in Table 4.2, static, kinematic, semi-kinematic, pseudo-kinematic and rapid static, may now be addressed.

Conventional Static

Static GPS using carrier phase observations and simultaneously occupying sites for an hour or more, is sometimes referred to as *conventional static GPS*, since it is the original technique used for GPS surveying. In this technique receivers track the same satellites simultaneously for at least one hour. One of the main reasons for occupying sites for over an hour (sometimes several hours) is to exploit the change in geometry as satellites track paths across the sky. It is this change in geometry which assists in ambiguity resolution and helps to improve the strength of solution.

The range of accuracy using conventional static GPS varies depending on the observing and processing procedures followed, the baseline lengths measured and the receivers used, among other variables. In very precise applications (e.g. for crustal motion studies, geodetic surveys etc.) sophisticated processing techniques which handle errors (Table 2.4) in special ways are employed. Using such techniques, accuracies of less than 1 cm rms have been achieved for baselines of up to 600 km in length.

Kinematic (Carrier based)

Kinematic techniques (Figure 2.9d) using carrier phase observations differ from those using code observations because they require that integer ambiguities be determined to achieve decimetre accuracies. Original kinematic GPS techniques required ambiguity resolution before moving, although means to determine ambiguities while moving (referred to as "on the fly") have recently been developed (e.g. Hatch (1991a & 1991b), Remondi (1991)).

Kinematic techniques are sometimes referred to as *continuous kinematic* (Kleusberg, 1990) or *pure kinematic* techniques. This differentiates kinematic from semi-kinematic techniques, which require stops at points to be positioned.

Kinematic GPS using carrier phase observations is usually applied to areas where the relation between physical elements and data collected in a moving vehicle are desired. For example, carrier phase kinematic GPS has been carried out in aircraft to provide coordinates for aerial photography (Merrell et al., 1990) and in road vehicles to tag and have coordinates for highway features (Lapucha et al., 1990).

Semi-Kinematic

Semi-kinematic GPS is also called *Stop and Go* GPS and was originally developed by Remondi (1985). This name perhaps better represents the physical conduct of this carrier GPS positioning method because the rover receiver stops at a point, and then goes to the next point and so on. The physical set-up for semi-kinematic GPS is similar to that of kinematic GPS in that one receiver is left stationary on a known point to serve as a *monitor* while a second, which serves as a *rover*, is moved between each point to be positioned. Before commencing movement of the rover receiver integer ambiguities of all satellites must be determined, and while moving the rover receiver must maintain lock on at least four satellites. The rover receiver is moved between each point, held stationary on the point to be positioned for up to tens of seconds, and then moved on to the next point to be positioned.

Several techniques exist to determine initial ambiguities. These include occupying a known baseline, an antenna swap procedure or a conventional static observation session. These are documented with most commercially available receiver packages which are capable of semi-kinematic GPS.

The main constraint with semi-kinematic techniques is the requirement to maintain lock on satellites while moving. If there is loss of lock, an observer may have to return to the last known site, where ambiguities may be determined once again. Obstructions in an area of work such as trees, bridges or buildings, may prohibit the successful application of semi-kinematic GPS. However in open areas, where accurate locational parameters for numerous points are sought, semi-kinematic GPS may be a viable alternative.

Pseudo-Kinematic

The name pseudo-kinematic GPS is somewhat of a misnomer because there is no kinematic aspect of pseudo-kinematic GPS. In pseudo-kinematic GPS, monitor and rover sites are used in a manner similar to kinematic and semi-kinematic GPS. However the rover receiver occupies each point for a few minutes twice, at least an hour apart. The receiver need not track satellites while moving from point to point and may actually be turned off.

The concept behind pseudo-kinematic GPS lies in ambiguity resolution. As previously mentioned, it is the change in satellite geometry over time rather than the number of measurements made which truly contributes to ambiguity resolution. Consequently, by combining two sets of data each a few minutes long, for the same point but spread over an hour apart, enough information is still present to resolve integer ambiguities and solve for a strong positional solution.

Pseudo-kinematic positioning has not seen wide-spread use due to the logistical constraint of having to return to the same point twice, spaced over an hour apart. In many cases conventional static or rapid static positioning prove to be better choices.

Rapid Static

The term *rapid static* was coined to describe static GPS positioning procedures which require minutes instead of hours of observations. The technique relies on successfully resolving carrier integer ambiguities over very short time periods. Methods to resolve ambiguities over such short time periods without benefiting from the change in satellite geometry over time, rely on additional information and sophisticated processing methods. This additional information may take the form of

P code observations or redundant satellites (e.g. seven or eight satellites instead of the minimum four).

Rapid static surveys should be conducted over short baselines (e.g. less than 10 km). Achievable accuracies are usually at the few centimetre level (rms). Most commercially available rapid static systems currently rely on P code observations. This is unfortunate because receivers which collect P code observations are generally more expensive than those which collect C/A code data, and P code data is scheduled to be unavailable for civilian use by the end of 1993. Manufacturers are now striving to develop techniques which avoid dependency on P code observations.

Rapid static GPS positioning is similar to semi-kinematic positioning in that monitor and rover receivers are used, but it is not burdened with the logistical need of having to track satellites while moving between points to be positioned.

CHAPTER 5
GPS PROCEDURES

Although GPS positioning techniques vary significantly as discussed in Chapter 4, their procedures may be grouped into four common phases: planning and preparation; field operations; data processing; and final reporting (Figure 5.1). Validation and reconnaissance form an integral part of the planning and preparation phase.

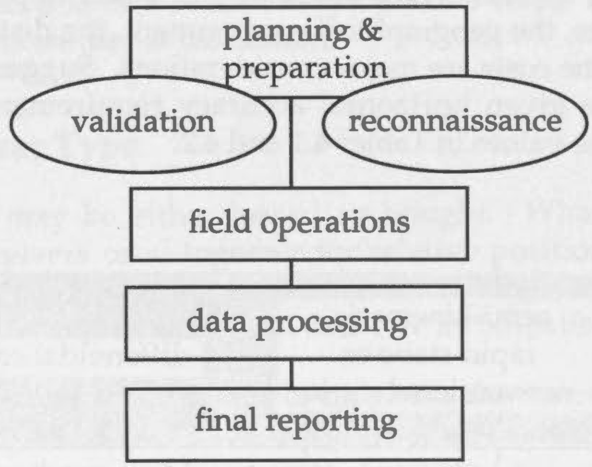


Figure 5.1 GPS Project Phases

In this chapter, components of each of these phases are explained, followed by a discussion of the special considerations which must be given to the use of GPS in the determination of orthometric heights.

5.1 PLANNING AND PREPARATION

Planning and preparation for a GPS field project begins with the identification of positioning requirements and ends with complete readiness for successful field operations. The extent of all the intermediate steps varies greatly with the magnitude, accuracy and locality of the project.

As a preliminary step, the points to be positioned and their accuracy requirements should be identified. Then, the sites to be positioned and the available survey control should be plotted on a map. EMR topographical maps at 1:50,000 and 1:250,000 are well suited for this purpose. Provincial and township road maps may also be very helpful. Maps show the approximate distances between points, site access information, and the potential for obstructions and interference. They serve as a reference throughout the planning, project execution and final reporting stages.

Important steps within the planning and preparation phase which follow, include selection of positioning technique, selection of receiver type, validation, reconnaissance, survey design and preparations. As will be seen, many of these planning steps are quite interdependent.

Selection of Positioning Technique

There are many aspects which influence the choice of positioning technique. Accuracy requirements, the geographical environment, the distance between points to be positioned and the costs are major considerations. Suggested GPS positioning techniques to achieve given horizontal accuracy requirements are presented in Figure 5.2, based on the values in Tables 4.1 and 4.2.

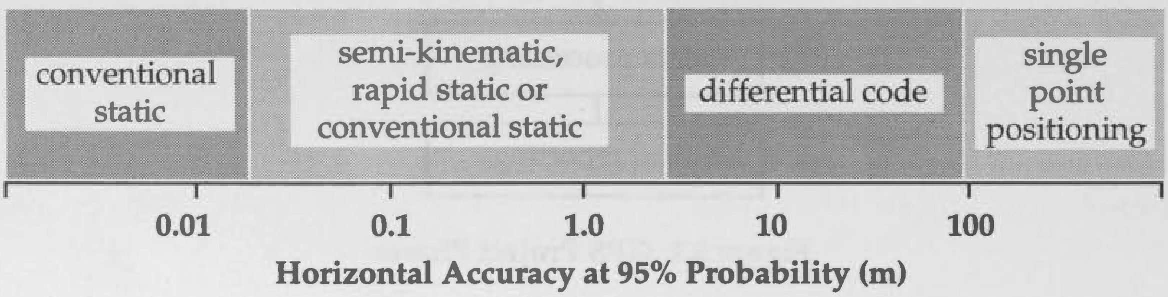


Figure 5.2 Suggested GPS Techniques For Required Horizontal Accuracies

Note that the figure shows the technique which should be used to achieve a given accuracy rather than the technique's accuracy range. For example, although a differential code solution may be accurate to between say 3 to 12 m depending on baseline length, if anything better than a 100 m accuracy is desired, a differential code solution should be used rather than a single point solution.

The suitability of using semi-kinematic, rapid static or conventional static GPS surveys for a project requiring sub-decimetre to metre level accuracy depends on the nature of the site being observed and the interstation spacing. Semi-kinematic surveys are the most restrictive as they require freedom from obstructions while moving from point to point. Consequently, semi-kinematic surveys would be suitable in a case where there are a large number of points to be positioned in an open area, such as a large field. Rapid static surveys should generally be limited to short baselines, if centimetre level accuracy is desired. For both semi-kinematic and rapid static surveys, the chance of success is much greater if at least six satellites are observed. For high accuracy over longer distances or in cases of weak satellite geometry, it may be wiser to use conventional static GPS techniques.

Note that Figure 5.2 shows techniques for horizontal accuracies rather than vertical accuracies. The corresponding vertical accuracies vary depending on whether ellipsoidal or orthometric heights are sought. Their relation to Figure 5.2 is addressed in Section 5.4.

The cost of GPS positioning is closely tied to the technique used, which in turn is chiefly a product of the accuracy requirements. Two major reasons for cost variations with technique are the time on site requirements and the cost of the required receivers. Generally, the shorter the time required on site, the lower the survey cost. The selection of a receiver type and its costs, to satisfy a required positioning technique is worthy of discussion.

Selection of Receiver Type

GPS receivers may be either leased or bought. Whatever the case, it is suggested that all receivers used together for relative positioning be of the same make to avoid problems which often result from mixing receiver types such as biases, complexities in data processing and data rate incompatibilities.

The receiver used must be capable of collecting the measurements needed for the desired positioning technique. Table 5.1 gives a brief summary of the part of the GPS signal required for the varied techniques. For both single point positioning and code differential positioning, a receiver which uses code measurements is all that is needed. (Note that some receivers use carrier measurements to smooth the code measurements and improve the resultant accuracy. This technique is primarily used for kinematic surveys.)

For semi-kinematic, rapid static and conventional static GPS surveys, code and carrier measurements are required. For short baselines using conventional techniques, single frequency receivers are sufficient. For conventional static GPS over longer baselines where high accuracies are sought, dual frequency receivers are desirable since they permit correction of most of the ionospheric errors. For rapid static surveys, dual frequency receivers are strongly recommended since they enable sophisticated data handling methods for ambiguity resolution and hence a much greater opportunity for success.

Table 5.1 GPS Measurements Required for Varied Positioning Techniques

Methodology	GPS Measurements Required
Single Point Positioning	code
Code Differential	code
Semi-kinematic	code & carrier
Rapid Static	code & carrier, dual frequency preferable
Conventional Static	code & carrier, dual frequency for long baselines

Representative costs for receivers which collect code, L1 code and carrier, and dual frequency measurements are shown in Figure 5.3. The broad range of prices for L1 code and carrier receivers and dual frequency receivers may mainly be attributed to receiver features other than just the type of measurements collected.

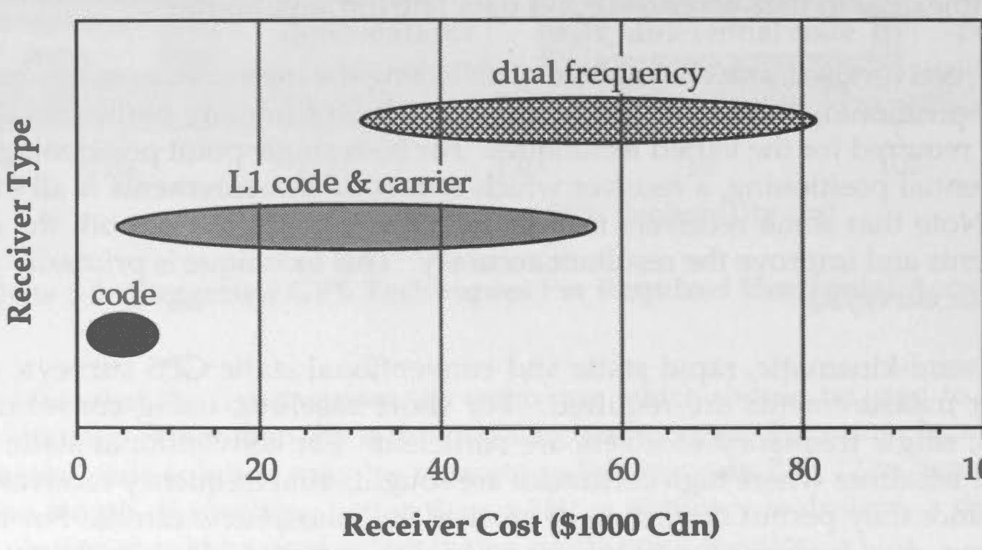


Figure 5.3 Representative Receiver Costs, January '92

The cost representation in Figure 5.3 is very general, and produced with the intent of demonstrating the significant difference in costs as one moves from low accuracy positioning using just code measurements to higher accuracy surveys requiring carrier measurements and possibly dual frequency receivers. The information used in this graph was extracted from a receiver survey published by

GPS World (Arradondo-Perry, 1992). For specific detailed information on receiver costs, one may refer to price surveys such as this one which are published on a regular basis. A trend of decreasing prices for GPS receivers has been experienced and can be expected to continue.

Receiver selection can be a complex process due to the large number of GPS receivers now available and their wide range of capabilities and intended applications. To assist in receiver selection, Figure 5.4 lists many elements which should be considered. This list is by no means exhaustive and is intended only to serve as a guideline. Naturally, the priorities for each aspect will vary depending on the desired application.

Technical Considerations
- type of measurement collected
- single or dual frequency,
- method used to collect L2 carrier
- sequencing or parallel channels
- number of channels
- antenna type and noise characteristics
- accuracy of code / carrier measurements

Field Suitability
- weight
- size
- ruggedness
- operating temperature
- power requirements

Accompanying Software
- satellite prediction
- downloading capability
- post processing options

Data Logging
- is there data storage?
- raw data or final product stored?
- data rate (s)
- storage method
- data storage capacity
- downloading method
- type of data which is downloaded

Business Considerations
- warranty
- costs
- technical support

Receiver Operation
- ease of use
- intended application(s)
- ability to monitor tracking status
- ease of entering station number

Figure 5.4 Aspects to Consider in Receiver Selection

Some aspects of the "technical considerations" listed in Figure 5.4 are worthy of explanation. These are the methods to collect the L2 carrier, the number of channels and the measurement accuracies.

There are different types of dual frequency receivers, distinguished by the method they use to collect the L2 carrier which in turn differentiates the quality of the resultant L2 carrier measurements. The highest quality L2 carrier measurements are collected by receivers which also collect the P-code. Since P-code will be unavailable to civilian use, several manufacturers have been developing alternative techniques to acquire high quality L2 carrier data. These techniques should be investigated when selecting dual frequency receivers.

Another important technical consideration which differentiates receivers is the means in which the receiver tracks numerous satellites at the same time. Two of the techniques used are sequencing and parallel channels. Using sequencing techniques, two or more satellite are tracked consecutively on the same channel. One satellite is tracked for a short time period, then the next one and so on, until the first satellite is tracked again. A shortfall with sequencing receivers is difficulty maintaining lock on a satellite throughout the sequencing process, leading to less reliable positioning. With parallel channels, the receiver continuously tracks satellites at the same time, with a channel designated to each satellite. Receivers with parallel channels are generally better at maintaining lock than those with sequencing channels. For a single frequency receiver with parallel channels, the number of satellites which may be tracked is usually equal to the number of channels. As known from the discussion of satellite geometry in Section 2.4, the more satellites tracked simultaneously the better. Ideally a receiver will have enough channels (eight or more) to track all satellites in view.

The last technical consideration which will be mentioned is the accuracy of the code and carrier measurements. All accuracies given in Tables 4.1 and 4.2 are general guidelines of what may be achieved using various techniques. This however does not suggest that all receivers using the same methodology will produce results of equal quality. One cause for the variation in achievable accuracies is the accuracy with which a receiver can measure the code and carrier measurements.

The remaining aspects to consider for receiver selection are more straight forward and will not be discussed. One very important step in assessing receiver types as well as methodology and processing is the validation process.

Validation

In the planning phase of a GPS project the procedures and equipment to be used, from data collection to the final product, should be tested to ensure they reliably satisfy the desired accuracy requirements. This testing is referred to as the validation process. If a user has previously successfully employed the same GPS procedures and equipment for a similar application, revalidation may not be necessary.

Three main components are tested in the validation process: the positioning technique chosen, the equipment to be used and the processing method adopted. The positioning method chosen may be one described in Chapter 4, or may be a newly developed procedure. Whatever the case, the method should be checked to ensure it will reliably satisfy user requirements. The equipment used for GPS varies greatly in complexity, cost and capabilities. It cannot be assumed that all accuracy claims given by equipment manufacturers or other users will be consistently met under all production field conditions, and hence it is important to test and evaluate the equipment. For the same reasons it is also important to test and evaluate GPS processing software and techniques.

The validation process also has the benefits of enabling users to identify and solve problems before commencing costly production surveys, to streamline operations, and to verify the accuracies which can be expected using the tested procedures. The validation concept is summarized in Figure 5.5.

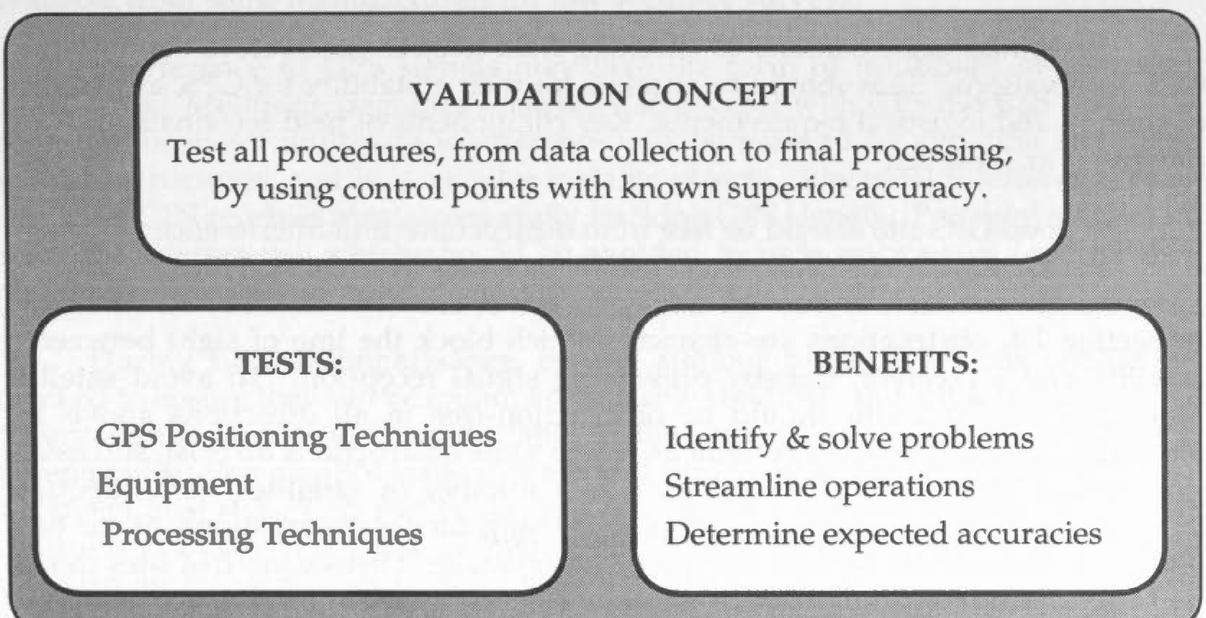


Figure 5.5 Validation Concept

Validation testing should be carried out using points with coordinates known to an accuracy superior to that desired for the project. The distance between points should be representative of that planned for the actual survey execution.

To provide a standard upon which GPS surveys may be tested (and in particular high accuracy surveys), the Geodetic Survey Division in cooperation with provincial agencies, has established several GPS basenets across the country. Each of these basenets consists of six to eight stations marked with forced-centring pillars, with interstation distances ranging from 2 to 50 kilometres in most locations. In addition, each basenet includes an electronic distance measurement (EDM) calibration baseline which provides a selection of shorter baselines. The Geodetic Survey Division may be contacted for information on Canadian basenets.

Other alternatives exist for providing control for validation surveys, particularly for lower accuracy surveys. For example, existing high accuracy control monuments may be used. Descriptions, coordinates and accuracy information for control monuments in a given area may be acquired from the Geodetic Survey Division. (See Appendix D.)

Validation is an important evaluation and feedback step in the project plan. An equally important step which gives feedback in the planning process is field reconnaissance.

Reconnaissance

Reconnaissance consists of checking field project sites before commencing GPS observations. Sites should be checked for their suitability for GPS, availability of control, and logistical requirements. Key components of field reconnaissance are presented in Table 5.2.

A good GPS site should be free from obstructions and interference. Through field reconnaissance, obstructions or interference may be identified and avoided by alternate site selection or through establishment of eccentric stations. As discussed in Section 2.4, obstructions are obstacles which block the line of sight between a satellite and a receiver, thereby preventing signal reception. To avoid satellite blockage, ideally a site should be obstruction-free in all directions above 15 elevation. In less than ideal conditions where some obstructions do exist, successful positioning may be possible if a sufficient number of satellites with adequate geometry can still be tracked. For surveys using carrier observations, or for base stations in differential surveys using code observations, obstruction-free sites should be sought. Code positioning techniques are generally more forgiving than carrier techniques to obstructions, since they are not subject to *cycle slips* (Section 2.5).

Table 5.2 Field Reconnaissance

Check Suitability for GPS	- free of obstructions? - free of interference?
Verify Control	- stations located? - monuments in stable condition?
Identify Logistical Requirements	- transportation method? - access time? - special equipment or procedures?
Take Action	- choose alternate sites if needed - establish eccentric stations if needed - note findings - update descriptions if required

Note that the elevation angle of obstructions should be considered with respect to the proposed height of antenna rather than ground level. Typically an antenna on a tripod has a height between 1 and 1.5 metres. However, poles designed to raise antennas to much greater heights to avoid obstructions are available from some manufacturers for low accuracy surveys.

Interference of GPS signals may take the form of multipath or electrical interference. *Multipath*, degrades accuracies achievable with GPS (Section 2.5). The potential for major multipath interference may be reduced by avoiding sites near artificial structures, and in particular metallic objects. Electrical interference may prevent a GPS receiver from successfully tracking GPS signals. Potential sources of electrical interference which should be avoided include microwave transmitting stations, radio repeaters and high voltage power lines.

During field reconnaissance, control stations planned for use should be checked to ensure they can be found, are in stable condition and are suitable for GPS observations. If control is unavailable in the area of interest to support, say a differential survey monitor station, one may desire to establish a new point through a conventional static GPS survey using control in the surrounding area. If vertical control is available in the area of interest but unsuitable for GPS, one may desire to establish an eccentric control point which would be suitable for GPS by levelling between the existing and newly established points. Whatever the case, one must be aware that the accuracy of the eccentric control point is only as good as the method used to tie the eccentric station to the original station.

Reconnaissance also provides much needed information on logistical requirements. The method of transportation and the time required to walk in to each point has significant implications for both the cost and logistics of a given survey. Similarly, any constraints which can be identified will facilitate successful planning. For example, the suitability for semi-kinematic or rapid static surveys may be assessed, the need for extra-tall poles to mount the antenna on may be realized, or the need for safety precautions for certain sites near roadways may be identified.

The final product of field reconnaissance will include a set of points ready for GPS observations as well as a current description for each site, access information and a description of any special steps which need to be taken.

Survey Design

Another important step in the planning and preparation process is the survey design. Considerations in the survey design include control requirements, network configuration and redundancy. Obviously, the survey design will vary greatly depending on the accuracy sought and the GPS positioning technique employed. Table 5.3 summarizes the control requirements and network configuration for various types of positioning.

Table 5.3 Control Requirements and Network Configuration

Technique	Control Requirements	Network Configuration
Single Point	none	not applicable
Differential	1 or more 3D points	radial
Conventional Static	3 or more 3D points (or equivalent)	closed geometrical figure
Rapid Static & Semi-Kinematic	varies	varies

In single point positioning, control points are not required (Section 2.3). Since this type of positioning is absolute instead of relative, network configuration does not apply and only one receiver is required.

Differential positioning requires at least one three-dimensional control station. This control point should have well determined NAD83 coordinates (Section 3.3) as well as an ellipsoidal height (Section 3.2). Differential surveys therefore typically take on a radial network pattern as illustrated in Figure 5.6.

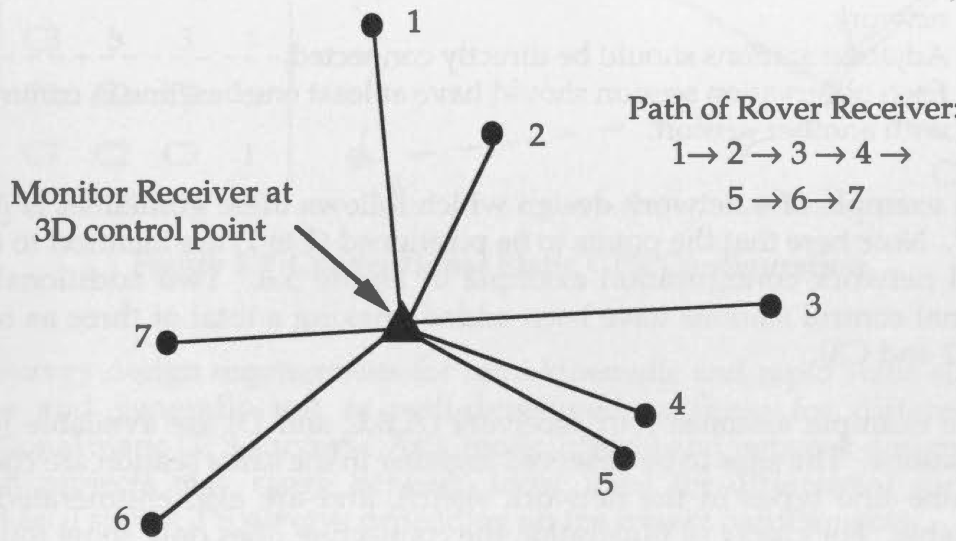


Figure 5.6 Radial Network Configuration

As shown in the figure, the monitor receiver tracks continuously at the three-dimensional control point as the rover receiver is moved to each point to be positioned (i.e. from 1 to 2 to 3 etc.). Direct connections are made between each point and the control point rather than between adjacent points. (Two points are directly connected if GPS observations are collected at each point simultaneously and processed together.) As a result, the relative accuracy between adjacent unconnected points will be quite poor.

This concept can be better explained by directly referring to Figure 5.6. Here, the relative accuracies between point 4 and the control point and point 5 and the control point would be good because each is directly connected, whereas the relative accuracy between points 4 and 5 would be poor since they are not directly connected. The weakness of the radial network configuration does not pose too much of a problem for differential positioning because of the low accuracy of differential positioning.

For conventional static GPS surveys, at least three control stations known three-dimensionally or an equivalent combination of horizontal and vertical control stations should be used.

Closed geometrical figures should be used for the network configuration of conventional static GPS surveys. Guidelines for designing such networks for static surveys are given in "Guidelines and Specifications for GPS Surveys" (Geodetic Survey Division, 1992) and include the following:

1) Each station must be directly connected to at least two others in the network.
2) Adjacent stations should be directly connected.
3) Each observation session should have at least one baseline in common with another session.

An example of a network design which follows these guidelines is given in Figure 5.7. Note here that the points to be positioned (1 to 7) are identical to those of the radial network configuration example in Figure 5.6. Two additional three-dimensional control stations have been added, making a total of three as required (i.e. C1, C2 and C3).

The example assumes four receivers (A,B,C and D) are available for each *observing session*. The sites to be observed together in the same session are connected by the same line types in the network sketch, and are also enumerated in the adjacent table. For clarity of illustration the connecting lines only show four out of the six direct connections made with each observation session. For example, for session 1, C1 to 2 and 1 to 7 are direct connections which are not shown.

Sessions 6 and 7 from the table are not illustrated in the network sketch of Figure 5.6, again for clarity. These sessions may or may not be used, depending on the desired thoroughness and redundancy of the observations. These last two sessions serve two purposes. First, by including these last sessions, each station is observed at least twice, providing redundancy and a means to detect blunders. Second, all horizontal control points are directly connected. This is useful for high accuracy surveys to control errors which may result from using horizontal control less accurate than the GPS survey.

There are many alternate ways to design the geometrical network shown in Figure 5.7. The intent here is to explain the concept behind network design rather than give steadfast rules. Logistical constraints detected from map and field reconnaissance will greatly influence the pattern of sessions designed, as will the number of receivers used, personnel available and so on.

Sess.	Receivers A	B	C	D
1	C1	1	2	7
2	C2	3	2	7
3	C2	5	6	7
4	C2	5	3	4
5	C3	5	3	4
6	C1	C2	C3	6
7	C1	C2	C3	1

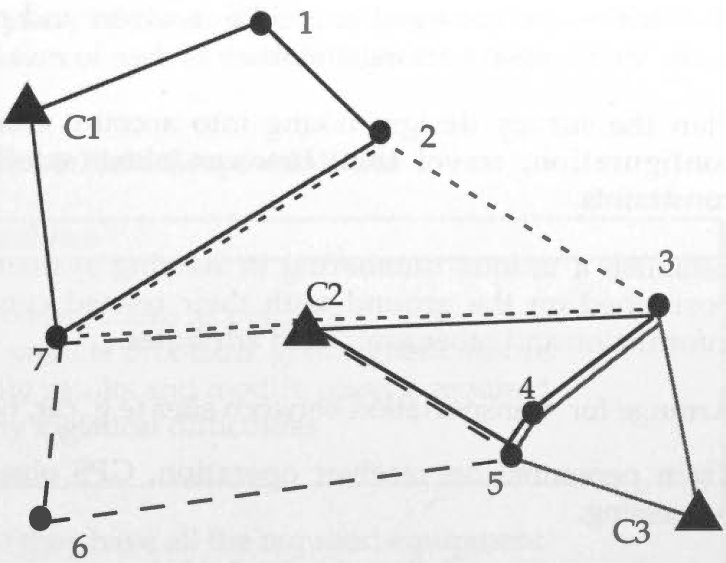


Figure 5.7 Conventional Static GPS Configuration

Survey design requirements for semi-kinematic and rapid static surveys are variable and generally not as well-developed as those for differential and conventional static GPS surveys. As a result, control and network design elements for such projects may range between those used for differential surveys and conventional static GPS surveys depending on the project requirements.

From an operational point of view, the radial network configuration is the most appealing since the rover can quickly and easily be moved between adjacent points while a monitor receiver is set-up on a control point. From an accuracy point of view, the radial approach is less desirable because of its potential to reduce relative accuracies between unconnected adjacent stations. A compromise between the two network techniques, perhaps better suited for semi-kinematic and rapid static surveys, would be to have two or more monitor stations and one or two rovers. Work still needs to be done in this area.

Preparations

Up to this point most of the main segments in the planning and preparation phase have been presented: the selection of positioning method and receiver type, the validation and reconnaissance processes, and the survey design. Several aspects of preparation have yet to be mentioned and so are listed below.

Determine the best *window(s)* available to collect GPS data based on satellite availability and geometry. (See Section 2.4.)

Decide the optimal number of GPS receivers and personnel for the project and make the necessary arrangements.

Plan the survey design, taking into account control requirements, network configuration, travel time between sites, satellite window and logistical constraints.

Establish a unique numbering or naming system to clearly identify all sites positioned on the ground with their related computer data files, positional information and other associated attributes.

Arrange for transportation between sites (e.g. car, helicopter, boat, or foot).

Train personnel on receiver operation, GPS observing procedures and data processing.

Organize accommodations for the field if required.

Organize all required equipment and supplies to support GPS field activities.

A special note should be made regarding training in receiver operations. Many receivers have options beyond those required for a specific application. Since manuals give instructions on how all the components of a receiver work, rather than just those of interest, it is recommended that a set of condensed customized instructions be developed, specifying exactly how the receiver should be used in the field. Thus each observer should be equipped with specific instruction sheets as well as the receiver manuals (to cover queries and trouble shooting which would not form part of an instruction sheet).

A wealth of information may be overlaid on the project map making it a rich reference source for field preparation. The base map would show control points and stations to be positioned, labelled appropriately. One layer may include logistical constraints noted in the reconnaissance. The next may show the network design marked with different colours for each session (similar to Figure 5.7), and the final layer may show sessions actually observed in the field.

Planning and preparation ends with complete readiness for successful field operations.

5.2 FIELD OPERATIONS

With good planning and preparation, field operations should be relatively smooth. Responsibilities in the field are typically divided amongst a party chief, observers and a processor. Depending on the magnitude and methodology of the project, these three groups of responsibility may all be assigned to one person or shared amongst many. A summary of some of the main responsibilities in the field is given in Table 5.4 and discussion of each of these follows.

Table 5.4 Field Responsibilities

	Responsibilities
Party Chief	schedule observations as per plan check for satellite problems, geomagnetic storms assess daily results and modify plans if required handle any logistical difficulties
Observers	check that they have all the required equipment ensure receiver battery is fully charged allow ample time to travel to site verify correct station is being occupied level, centre and orient GPS antenna over marker measure antenna height initialize receiver monitor receiver operation and data recording complete station log sheet submit data and log sheets to processor at end of day
Processor	verify data submissions download data make backups of raw data organize all data (data management) process GPS data adjust all sessions together if applicable check results and report to party chief

Party Chief Responsibilities

The party chief's responsibility is to ensure all crew members have the training, equipment and information required to carry out observations according to plan. Daily field duties may include: (1) scheduling who should observe at what station when, (2) keeping informed of any satellite problems or *geomagnetic storms*, (3) assessing results on a daily basis and modifying plans as required, and (4) handling any logistical difficulties.

The schedule of who should observe at what station when is very important with GPS because observations should be carried out at times of optimal satellite geometry and simultaneous observations at different sites are essential for relative positioning. The daily scheduling should systematically follow the planned survey design (e.g. Figures 5.6 or 5.7). The schedule should tell each observer where to be at what time and for how long. Descriptions (from the reconnaissance) should be available for the observers to locate their station. If several sessions are observed in one day, sufficient time should be allowed between sessions for safe travelling between stations. If communications may be maintained between all observers and the party chief in the field (perhaps through the use of cellular phones), the planned session may be modified in the field according to reported progress.

From time to time satellite problems and geomagnetic storms can affect successful GPS positioning. Information about satellite status may be attained from the GPS Information Center (See Appendix B). This information may be used in advance to modify observing schedules if necessary. For example, if a satellite planned for use is set unhealthy, new satellite prediction information could be computed omitting this satellite, and the planned observation schedule could be modified accordingly.

The ionosphere can also pose problems for GPS applications, particularly in high latitudes in the auroral zone (see Appendix C) where geomagnetic activity is very active. Recall from Section 2.5 that the ionosphere is a layer of free electrons which causes errors in the measured GPS signals. This layer of electrons is more irregular in the northern regions. Occasionally geomagnetic storms, marked by a much heightened level of ionospheric irregularities, extend to more southern latitudes and play havoc on GPS observations. Thus the party chief should be aware of any geomagnetic storm activities and plan accordingly. Geomagnetic activity predictions for Canada may be attained from the Geomagnetic Forecasting Service of the Geophysics Division, EMR. (See Appendix C.)

GPS observations should be downloaded and processed immediately after the observation session to ensure data collection was successful. If the collected data does not meet standards, reobservations may be needed.

The party chief must make provisions for any logistical constraints which present themselves throughout a field project. Such constraints may range from difficulties accessing a station to a receiver breakdown. The more prepared the party chief and crew are before the project begins, the more easily they will be able to adapt to unexpected happenings in the field.

Observer Responsibilities

Once the observing schedule has been specified by the party chief, the observer should know where, when and for how long GPS observations should be collected. Observer field responsibilities may be broken down into four stages:

preparation for observations, set up in the field, monitoring receiver status and terminating observations.

The preparations required before heading out for a day's observations are straight forward, but could lead to failure if not carefully executed. Observers should plan their route and generously estimate the time required to travel to their site(s). All required equipment, site descriptions and log sheets should be assembled. Receiver batteries should be fully charged.

At each site in the field, the observer has a series of steps to follow to prepare for GPS observations. First, it should be verified that the site is indeed the correct site. A sketch showing the wording and numbering stamped on the monument (if applicable) may be prepared to serve as a validation in the office that the correct site was occupied.

The next step involves setting up the GPS antenna over the marker and measuring the antenna height from the antenna phase centre to the marker. The accuracy requirements for centring an antenna over a survey marker varies with the GPS positioning method being used. Obviously, there is no benefit in centring a rover antenna for a differential survey over a marker to the nearest few millimetres if only a few metres accuracy can be expected.

For high accuracy surveys, the GPS antenna should be centred over the marker with the aid of a tribrach, on a tripod. The tribrach enables levelling of the antenna and precise centring over the survey marker. The tribrachs used should be regularly checked to ensure they are well calibrated. Most antennas designed to collect carrier phase observations will have some "north" indicator on their casing. This indicator should be oriented to north for all antennas which collect data simultaneously. This common physical orientation of all antennas helps to minimize biases which may result from phase centre variations in antennas of the same make.

Measurement of antenna height is a responsibility of the observer which requires particular attention because of the potential for blunders. The antenna height is the vertical distance between the marker and the phase centre of the antenna. Most measurements of antenna heights are carried out in two steps: the vertical distance from the survey marker to the base of the antenna is measured, and the known height (as provided by the manufacturer) between the antenna base and the antenna phase centre is added. (See Figure 5.8.)

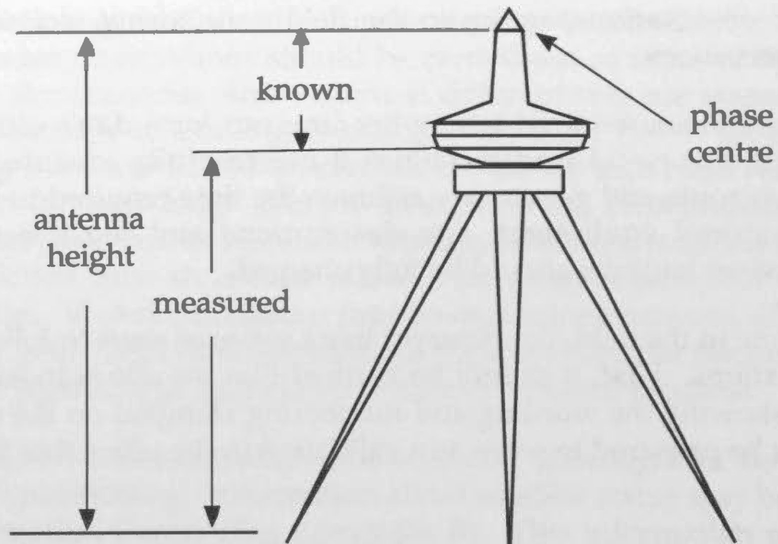


Figure 5.8 Antenna Height Measurement

Most receivers have some pre-established method for measuring antenna heights. On occasions where it is not possible to make direct vertical measurements, slant height measurements may be made and then the vertical distance may be computed using Pythagorus' theorem. That is

$$\text{measured height} = \sqrt{(\text{slant height})^2 - (\text{antenna radius})^2}. \qquad (5.2)$$

In all cases, redundant antenna height measurements should be made. If slant heights are used they should be measured on each side of the antenna. Antenna heights should be measured at both the beginning and the end of the observation periods. Regardless of how the antenna height is measured, the method used should be clearly recorded to prevent any misinterpretation by the processor.

For some differential, semi-kinematic and rapid static surveys, the antenna at the monitor and rover sites may be fixed on a pole of constant height which enables approximate levelling over the site through a bull's-eye bubble. In such cases, the antenna height need not be measured per se since it should be the same at all points, and cancel out in differencing.

Once the antenna is properly centred and the antenna height measured and recorded, the receiver should be initialized for data collection following the prepared instructions. The next task of the observer is to ensure the receiver is working without difficulties. This may include verifying on the receiver display that satellites are being tracked and data is being recorded.

It is very important that observers keep a comprehensive field log for each site. This provides the only record on conditions noticed in the field or difficulties experienced. Information which should be documented includes:

- site name and identifier for the receiver data file,
- observer's name,
- receiver and antenna types and serial numbers,
- antenna height and an explanation of how it was measured,
- data collection start and stop times,
- satellites tracked and
- problems experienced and actions taken.

A sample of a GPS field log for conventional static GPS surveys is shown in Appendix F. The format of this log, whether paper or computerized, may vary depending on requirements.

Upon terminating observations, the observer should ensure data has been recorded, recheck the antenna height and centring, shut down and pack up equipment as per the receiver instructions and finalize the field log sheet. After returning from a day of observations, each observer should turn over the field log and collected data to the processor.

Processor Responsibilities

It is important to process GPS data immediately after data collection to identify problems while it is easy to remedy them. This data processing may take place on a computer set up in a hotel room if field operations are being conducted out of town, or back in the office for the case of local surveys.

The field processor's duties commence as soon as data and field log sheets are returned from the day of observations. Data submissions should be verified to ensure they are clear, complete and accurate. Then data should be downloaded from the receiver or its data storage media to the computer and backups should be made of all raw data. A system of effectively managing the large quantity of data returns and data backups should be established and maintained.

The field processor should as a minimum, carry out sufficient proccessing to judge if the data collected is of adequate quality for the applications. (Processing is discussed in Section 5.3.) The processor should analyze processing results to assess the goodness of the data, compare redundant measurements and so on, and pass the results on to the party chief to make decisions as to the need for any reobservations or revisions of plans.

The processor should also keep notes on the data processed, difficulties experienced and actions taken. This serves as a record of what was done with the data, when and why. Ideally, all data processing should be carried out in the field.

This however will not always be the case due to time constraints and the need for more rigorous processing.

5.3 DATA PROCESSING AND FINAL REPORTING

At this point the most critical GPS project phases (Figure 5.1) have been explained. The final data processing and reporting are not as time critical as the planning, preparation or field operations, but still must be given due attention for the overall success of the project. Data processing is described first, followed by a description of final reporting.

The complexity of data processing corresponds with the complexity of the GPS technique used. Single point positioning is the simplest, followed by differential positioning and then carrier techniques.

Most receiver purchases or rentals are accompanied by software for GPS processing. As well, several GPS processing packages are available commercially. Fortunately most of these packages are quite automated. Nevertheless, it is important for users to have a general idea of what is involved in GPS processing.

Most single point positioning solutions are computed within the receiver and displayed. The only post-processing activities which may be involved include downloading this data and combining it in a database or a geographically referenced information system.

For differential solutions using code observations, the data from the monitor site and all the rover sites must be loaded onto one computer. At the start of the processing program, the known monitor receiver NAD83 coordinates should be entered. The program will then match the times of the code observations made at each remote site with those made at the monitor site. By using the satellite ephemeris data, the know receiver coordinates and the code measurements, the program will compute the coordinates for each remote site. Note that by using the differential method following a radial network configuration, there are no checks on the solution unless a rover site is occupied twice, and the differences in the solutions are compared.

Processing for conventional static GPS surveys is more complex and may require combining several sessions of observations. All data for one session must be loaded onto a computer. As well, the appropriate "known" three-dimensional NAD83 coordinates of the control points should be entered in the processing program. Most software will also require that approximate coordinates for all other sites occupied during the session be entered. Such approximate values may be read off the same receiver used in the field, or may be scaled from a map.

For each session processed, most software will require one point be held fixed three-dimensionally. Ideally this point will be a control point with know NAD83 coordinates. If a control point is not included in a specific session, coordinates of a site in common with an adjoining session which was tied to a control point should be used.

In the GPS processing algorithm, models may be used to correct some of the biases in the observations. Then all the observations, the ephemeris data and the known coordinates will be combined together in an optimal way (know as an adjustment) to arrive at a solution. In the process, an attempt will be made to resolve all carrier phase integer ambiguities. If this can be correctly done, the resultant solution will be of higher accuracy. The solution will consist of coordinate differences between each station included in the session and the related accuracy information.

Much of the orbital errors described in Section 2.5, including those introduced by selective availability, may be significantly reduced if a *precise ephemeris* is used instead of a *broadcast ephemeris*. As was explained in Section 2.1, the broadcast ephemerides are based on predictions of where a satellite is in the sky at a given time. More precise determinations of the satellite's position are attained by tracking the satellites at stations around the world, combining this data and computing the position of where the satellites were in the sky. Using post-computed precise ephemerides can significantly improve accuracies for precise surveys. Precise ephemerides are available from the Geodetic Survey Division and the U.S. National Geodetic Information Center. (See Appendix B for details.)

To combine several sessions of information together into one solution, a network adjustment should be carried out using software designed for this purpose. The network adjustment combines all the coordinate differences from all the sessions of observations in an optimal manner. A few GPS manufacturer software packages also provide network adjustment capabilities. As well, several independent packages which can adjust GPS networks are available commercially. Note that for a network adjustment to be effective, the survey design requirements spelled out for conventional static GPS surveys in Section 5.1 should be followed. The initial network adjustment carried out should be minimally constrained (i.e. only one three-dimensional control point should be held fixed) to enable examination of GPS results without the influence of existing control.

The processing results of conventional static GPS may be checked by comparing redundant baselines, and through statistical tests in the adjustment process.

Techniques for processing semi-kinematic and rapid static data are still evolving and have similarities with both differential processing and conventional static processing.

Processing software has not been dealt with in any detail here as it is usually included with receiver rental or purchase and tends to be quite complicated.

However, a good summary of receiver package features is available in Hofmann-Wellenhof et al. (1992).

When all field operations and observations are complete, a final report of the project should be drafted, documenting the stations occupied, methods used and results attained. Perhaps the most important requirement for final reporting is the identification of any improvements which could be made in the procedures, for the next GPS positioning project.

5.4 DETERMINING ELEVATIONS USING GPS

To determine *orthometric heights* using GPS, the geoid undulation must be known (see Figure 3.5). Two factors affect the accuracy of orthometric elevations determined using GPS: the accuracy of the ellipsoidal height determined directly with GPS, and the accuracy of the *geoid undulation* derived from geoid models. The expected accuracy of the *orthometric heights*, σ_H, can be estimated by taking the square root of the sum of the squares of the ellipsoidal height accuracy, σ_h, and the *geoid undulation* accuracy, σ_N. That is,

$$\sigma_H = \sqrt{\sigma_h^2 + \sigma_N^2}\,. \qquad (5.2)$$

Ellipsoidal heights determined using GPS are generally less accurate than their corresponding horizontal components because of the limitations of the satellite geometry for vertical positioning. Moreover, some of the errors listed in Table 2.4 influence the vertical component much more than the horizontal component. As a rough guide, one can expect the ellipsoidal height accuracy, σ_h, to be 1.5 times that of the horizontal accuracy. (This factor will change with the geometry of the satellites and observing conditions.) General accuracy figures for ellipsoidal heights are given in Tables 4.1 and 4.2. As well, most adjustment solutions of GPS observations estimate the standard deviation for the vertical and horizontal components independently. Thus the determination of the ellipsoidal height accuracy σ_h, is relatively straight forward.

In contrast, the estimation of the geoid undulation, N, and its accuracy σ_N is more complex. Factors which affect the geoid undulation accuracy include whether absolute or relative positioning is applied, the type of geoid model used, the topography and geoid gradient in the region, and the baseline length. Each of these affect procedures to be used and accuracies achievable in determining orthometric heights with GPS, and so will be addressed accordingly.

As was explained in Section 3.2, determination of orthometric heights with GPS through absolute positioning (i.e. single point positioning) is straight forward. Through single point positioning, an ellipsoidal height with a vertical accuracy of 156 m at the 95% level is determined. To transform this ellipsoidal height to an orthometric height, one need only subtract the geoid undulation (as derived from a geoid model) from the ellipsoidal height. These geoid undulations can range up to 50 m in Canada and 100 m over the world, and so it is important that they are applied to attain orthometric heights, even for low accuracy single point positioning. Some receivers apply the geoid undulation internally in a manner invisible to the user.

For relative positioning, the required treatment of the geoid undulation varies depending on the accuracy of the survey being carried out. For these purposes, the geoid will be considered in two groups: low accuracy relative positioning surveys based on the code measurements (i.e. differential positioning) and high accuracy relative positioning surveys based on carrier measurements (i.e. conventional static, semi-kinematic and rapid static GPS). For the former, a crude geoid correction is sufficient, and for the latter, a more sophisticated procedure should be used. In both cases a detailed precise model should be used, such as the GSD91 in Canada.

For relative positioning, it is the change in the geoid undulation over spatial distance which is of concern rather than its absolute value. This change is referred to as the geoid gradient. Geoid gradients generally correlate with topographical features, with the smallest gradients occurring in flat regions such as the Canadian Prairies, and the largest gradients occurring in mountainous regions such as the Canadian Rockies. However one should be aware that there are other less obvious factors which affect the geoid gradient. In general, the smaller the geoid gradient, the more accurately relative orthometric heights may be determined using GPS.

Low Accuracy Orthometric Heights Through Differential GPS

For differential positioning, the monitor receiver is usually placed on a control point with known three-dimensional coordinates, i.e. latitude, longitude and orthometric height (H_m). The geoid undulation at the monitor site (N_m) is added to the orthometric height to arrive at the ellipsoidal height for that point (h_m), which is held as a constant in GPS processing. Through differential GPS, the ellipsoidal height for each rover site (h_r) is computed. The desired orthometric height at the rover site (H_r) is then calculated by subtracting the geoid undulation at the rover site (N_r) from the ellipsoidal height (h_r). This concept is illustrated in Figure 5.9.

The uncertainty in the relative geoid height σ_N using a crude geoid correction, following the procedures demonstrated in Figure 5.9, will vary with baseline length and the smoothness of the geoid gradient. Typical ranges for these uncertainties are shown in Table 5.5. Note from the table, that for 2-3 km and 1 km baseline distances in areas with large geoid gradients, the accuracy over distances under 3 km is marked as unknown - because it is unknown. Thus one would be wise to use the pessimistic 25 cm for σ_N in this case.

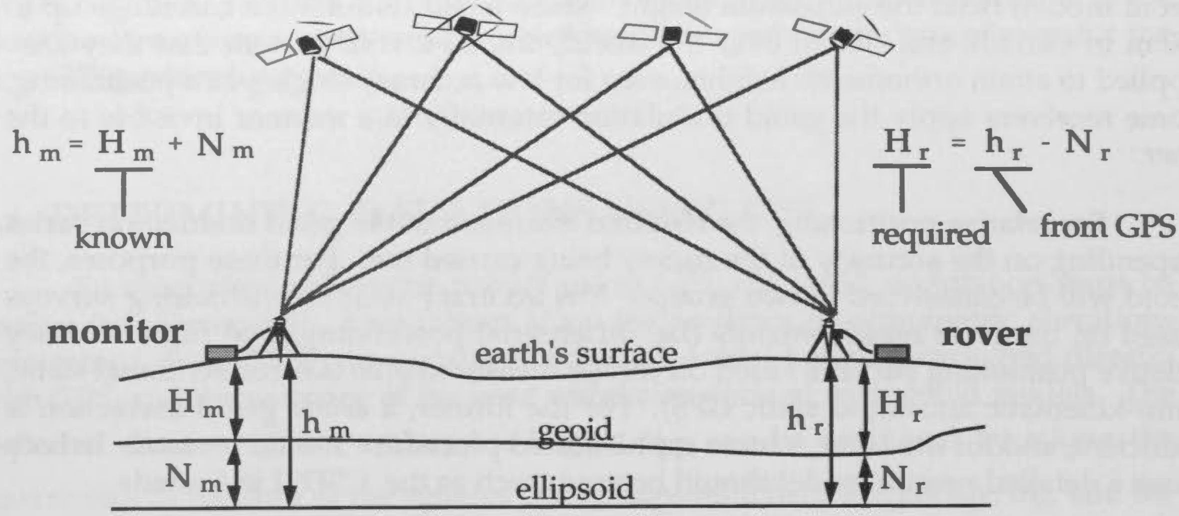


Figure 5.9 Determining Orthometric Heights Using Differential Techniques

Table 5.5 The Contribution of Relative Geoid Uncertainty in the Determination of Orthometric Heights Using GPS

Baseline Length	Geoid Contribution to Relative Height Errors (σ_N) (using a crude geoid correction and geoid model GSD91)	
	Flat or Small Geoid Gradient	Mountainous or Large Geoid Gradient
30-500 km	max. 25 cm	max. 1 m
5-10 km	max. 10 cm	max. 25 cm
2-3 km	max. 5 cm	do not know
1 km	max. 5 cm	do not know

The procedure shown for attaining orthometric heights using differential GPS is relatively simple. In fact, many receiver packages designed for differential GPS take care of the orthometric-ellipsoid height difference in a manner which is invisible to the user. Nevertheless, it is important that users of GPS understand what is happening and why. The error contributed by a commercial geoid model would likely be greater than those shown in Table 5.5 if a model other than GSD91 is used.

To arrive at higher accuracy orthometric heights and exploit the inherently more accurate relative carrier phase positioning techniques, the procedures which need to be followed are much more complex.

High Accuracy Orthometric Heights Using Carrier Phase Measurements

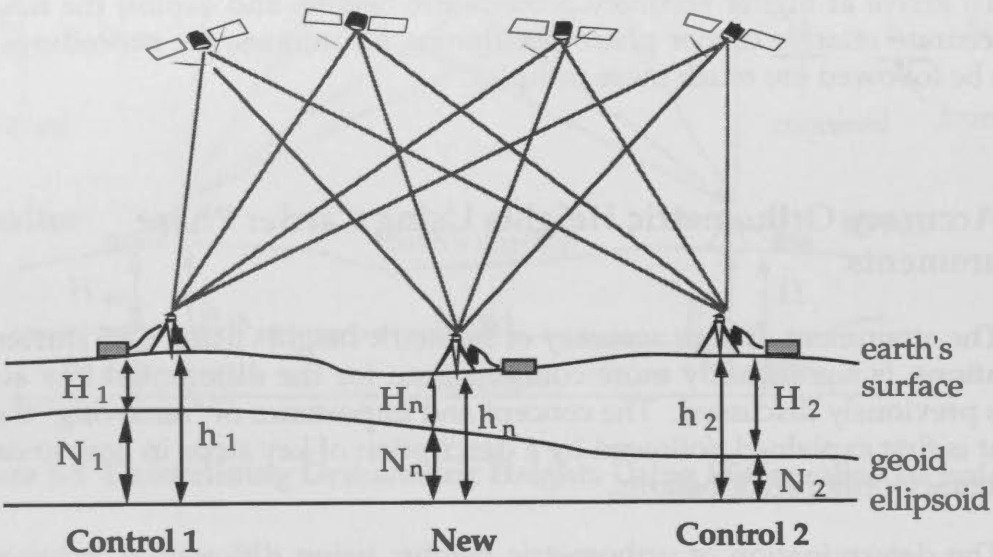
The attainment of high accuracy orthometric heights using GPS carrier phase observations, is significantly more complex than for the differential low accuracy surveys previously discussed. The concept and importance of "removing" the geoid gradient is first explained, followed by a description of key steps in how to compute high accuracy orthometric heights.

The determination of orthometric heights using differential techniques, as shown in Figure 5.9, uses only one known orthometric height (i.e. H_m at the monitor site). For more accurate orthometric height determinations, two or more orthometric heights on the periphery of the survey area should be known. The orthometric heights of the new points between them are then in essence interpolated. This has the effect of removing most of the geoid slope and enhancing the achievable accuracies.

The concept can be further explained with the aid of Figure 5.10. In the figure two points, Control 1 and Control 2, have orthometric heights H_1 and H_2 determined from first order levelling. The orthometric height for a new point H_n, is desired. From an accurate geoid model, such as GSD91, estimates of the geoid undulations N_1, N_2 and N_n can be found. From GPS observations, the ellipsoid height for all three points are measured (h_1, h_2 and h_n).

Note that at Control points 1 and 2, the ellipsoidal height h_1 and h_2 may be determined in two ways: directly from GPS observations and by summing the known orthometric heights and geoid undulations (i.e. $h_1 = H_1 + N_1$ and $h_2 = H_2 + N_2$). The ellipsoidal heights determined using these different methods will not be the same, mainly due to the limited accuracy of the geoid model. In fact, occupying bench marks with GPS provides a means for measuring the inaccuracy of the geoid undulation at that point.

To determine the orthometric height, H_n, the geoid undulation N_n is required (i.e. $H_n = h_n - N_n$). By using the measured inaccuracies of the geoid undulation at Control 1 and Control 2, one can interpolate between these and arrive at a more accurate N_n at the intermediary point. This is the concept behind achieving high accuracy orthometric elevations with GPS and can be thought of as using bench marks to correct for the geoid slope.



Known: H_1 and H_2
From Geoid Model: N_1, N_2 and N_n
Measured with GPS: h_1, h_2 and h_n
Required: H_n

Figure 5.10 Determining Orthometric Heights Using Carrier Techniques

Although the concept presented in Figure 5.10 may sound complex, it is actually implemented through the application of a least squares adjustment, by holding the points with known elevations from levelling fixed. Furthermore, more than the two control points shown in Figure 5.10 could be used. In fact three points would be preferable to take into account the geoid slope in a plane, not just a line.

When two or more bench marks are used to take the geoid slope into account, and the GSD91 is applied to attain geoid undulations, the resultant geoid accuracy, σ_N, as per equation 5.2, is shown in Table 5.6. In the table, representative values for σ_N over small and large gradients are shown. Over short distances (i.e. over less than a few kilometres), the geoid model does not provide enough detail to use different values at each point, and consequently the same undulation values may be used.

Table 5.6 Approximate Error in Relative Heights Determined Using Precise GPS Surveys Due to Geoid Uncertainty

Baseline Length	Geoid Contribution to Relative Height Errors (σ_N) (using GSD91)	
	Flat or Small Geoid Gradient	Mountainous or Large Geoid Gradient
30-500 km	σ 10 cm max. 20 cm	σ 20 max 50 cm
5-10 km	σ 5 cm max. 10 cm	σ 10 cm max. 20 cm
2-3 km	σ 2 cm max. 5 cm	do not know
1 km	max. 2 cm	do not know

In all cases at least two bench marks on the perimeter of the survey area should be occupied with GPS to compare ellipsoidal height differences (Δh) and orthometric height differences (ΔH). The geoid gradient, as evident from Δh - ΔH, will indicate if relative geoid accuracies shown in the above table are reasonable for the immediate area being considered.

One must always take geoid undulations into consideration when determining orthometric elevations using GPS. For determination of high accuracy elevations using GPS, great care and understanding must be taken in observations and data processing to minimize errors and cope with geoid uncertainties. Although this section has provided the fundamental concepts to determine high accuracy elevations with GPS, it is strongly recommended that the services of a person experienced in geodesy and GPS positioning be employed for such projects. There is a great risk of unknowingly achieving lower than desired accuracies if special procedures, which are beyond the scope of this document, are not followed.

[illegible]

[illegible]

Baseline Length	Geoid Contribution to Relative Height Errors Using GPS	
	Flat or Smooth Geoid Conditions	Moderate/Large Geoid Conditions
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]

In all cases at least two bench marks on the perimeter of the survey area should be occupied with GPS receivers to [illegible] orthometric height differences [illegible]. The geoid gradient, [illegible] will indicate if relative geoid accuracies shown in the above table [illegible].

[illegible]

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APPENDIX A
GLOSSARY

GLOSSARY

absolute accuracy the closeness of an estimate (or measurement) to the truth with respect to the earth's reference frame

absolute positioning the determination of the coordinates of a receiver with respect to the earth's reference frame by intersection of the signals from four or more GPS satellites (also referred to as *single point positioning* or simply *point positioning*)

accuracy the closeness of an estimate (or measurement) to its true (but unknown) value

alerts a table which indicates the positions of the satellites in view to an observer on the earth's surface at a designated location and time

almanac files data files which contain parameters describing the location of the GPS satellites with respect to time and which are needed to compute predictions of satellite availability, visibility and geometry

ambiguity the integer number of carrier cycles between a satellite and receiver

anti-spoofing (AS) the denial of access of the P code to civilian users

azimuth the horizontal angle clockwise from north to the location of the satellite in the sky

baseline a pair of *stations* for which simultaneous GPS data has been collected

blunders errors which result from some equipment malfunction or observer's mistake (also referred to as *gross errors*)

broadcast ephemerides a set of parameters which describe the location of satellites with respect to time, and which are transmitted (broadcasted) from the satellites

C/A code the GPS code which is freely available to civilian users, is referred to as the coarse acquisition code and is modulated on the L1 carrier at a frequency of 1.023 MHz

carrier frequencies continuous electromagnetic radiation of constant amplitude and frequency emitted by a radio transmitter; GPS satellites emit two carrier frequencies: L1 at 1575.42 MHz and L2 at 1227.60 MHz, which are biphase modulated by code and satellite messages

continuous kinematic type of GPS positioning where at least one GPS receiver continuously tracks GPS satellites while moving, with the objective of providing the position of the trajectory of the receiver (also referred to as *pure kinematic*)

conventional static GPS positioning method of relative positioning whereby two or more GPS receivers, each set up over a *station*, collect data from the same satellites simultaneously, for at least one half hour and more commonly at least an hour; it is by using this type of relative positioning with carrier measurements that the greatest potential accuracies may be achieved with GPS positioning

conventional terrestrial coordinate system an earth-centred coordinate system with the Z axis directed towards the north pole, the X axis passing through the plane which contains the Greenwich Meridian and the Y axis perpendicular to the X and Z axes to form a right handed system; can be used to describe the location of points on the earth or satellites in space

cutoff angle the *elevation angle* below which GPS signals are not recorded due to an option set in the GPS receiver or GPS processing software (also referred to as *mask angle*)

cycle slip an unknown jump in the number of carrier cycles resulting from failure to maintain continuous lock on a satellite

datum a point, line, surface or set of quantities used as a reference upon which measurements are based

differential positioning a type of *relative positioning* whereby measurements made at a known *monitor* point are used to correct measurements at an unknown *rover* point (occasionally in literature *differential positioning* is used interchangeably with the more generally defined *relative positioning)*

dilution of precision (DOP) a numerical indicator of the geometric strength of the satellite constellation in relation to positioning at a certain location and time

dual frequency receiver a receiver which is capable of tracking both L1 and L2 GPS carrier frequencies

elevation angle the angle from the GPS receiver's antenna between the horizontal and the line of sight to the satellite

ellipsoid a smooth mathematical surface which resembles a squashed sphere and is used to represent the earth's surface

geodetic coordinate system an earth-centred coordinate system where latitude is the positive angle from the centre of the earth northwards from the equator and longitude is the positive angle from the centre of the earth eastwards from the Greenwich Meridian

geoid the equipotential surface (i.e. the surface on which the gravity potential is constant) which best approximates mean sea level

geoid model describes the pattern of geoid undulations over the earth's surface as a function of latitude and longitude

geoid height the height difference between the *geoid* and *ellipsoid* at any given point on the earth's surface (also referred to as *geoid undulation*)

geoid undulation the height difference between the *geoid* and *ellipsoid* at any given point on the earth's surface (also referred to as *geoid height*)

geomagnetic storms occur when solar flares cause irregular ionization of the ionosphere which in turn causes irregular refraction delays of a radio wave passing through the non-homogeneous medium

gross errors errors which result from some equipment malfunction or observer's mistake (also referred to as *blunders*)

ground control segment the ground based system used to operate the satellites on a continual basis

ionosphere the layer of free electrons ranging from about 50 to 1000 km above the earth

ionospheric errors the delay resulting from GPS signals being transmitted through the ionosphere

kinematic refers to the type of GPS positioning where a receiver is moving while data is being collected

mask angle the *elevation angle* below which GPS signals are not recorded due to an option set in the GPS receiver or GPS processing software (also referred to as *cutoff angle*)

measurement method method of *differential positioning* whereby the measurements at the *monitor* site are used to correct the measurements at the *remote* site (see *position method*)

monitor refers to a stationary GPS receiver set up on a point of known coordinates, providing a basis from which measurements to the *rover* receiver may be referenced

multipath refers to a reflected signal that combines with a true signal resulting in a weaker position determination

observing session the time period during which simultaneous GPS observations are taken

obstructions obstacles which block the line of sight between a GPS receiver's antenna and a satellite

orbital error the difference between the satellite position as calculated using its ephemerides and its "true" position in space

orthometric heights heights above the *geoid* which have traditionally been determined through levelling

P code the precise GPS code which through *anti-spoofing* will be unavailable to civilian users; it is modulated on both the L1 and L2 carriers at a frequency of 10.23 MHz

point positioning the determination of the coordinates of a receiver with respect to the earth's reference frame by intersection of the signals from four or more satellites (also referred to as *absolute positioning* or *single point positioning*)

position method method of *differential positioning* whereby the measurements at the *monitor* site are used to compute a position, which is in turn used to correct the position computed at the *remote* site (see *measurement method*)

post-mission processing data processing to compute positions which is carried out after the *observing session* is completed

precise ephemeris a set of parameters which precisely describe the location of satellites with respect to time, which are based on computations of data collected from GPS tracking stations around the world

precision the closeness of an estimate to its mean estimate

probable error a magnitude of error which represents 50% uncertainty

pure kinematic type of GPS positioning where at least one GPS receiver continuously tracks GPS satellites while moving, with the objective of providing the position of the trajectory of the receiver (also referred to as *continuous kinematic*)

random errors the errors which remain if all *gross* and *systematic errors* are removed; random errors tend to be distributed about the mean following the normal probability distribution function

rapid static a form of static GPS positioning which requires minutes instead of hours of observations due to special *ambiguity* resolution techniques which use extra information such as *P code* measurements or redundant satellites

real-time processing positions computed as soon as data is collected

receiver clock errors errors due to the inaccuracy of the receiver clock in measuring the signal reception time

receiver noise a quantification of how well a GPS receiver can measure code or carrier observations

relative accuracy the accuracy of a measurement between two points (i.e. the accuracy of one point measured relative to another)

relative positioning the determination of the position of one point with respect to another point with known coordinates

remote refers to a GPS receiver which either moves along a trajectory to be positioned (e.g. for *kinematic* positioning) or from point to point to be positioned (e.g. *semi-kinematic* or *rapid static*), and whose measurements are combined with those from a *monitor* receiver for *relative positioning* (also referred to as a *rover*)

root mean square (rms) measure of the dispersion of observations about the mean

rover refers to a GPS receiver which either moves along a trajectory to be positioned (e.g. for *kinematic* positioning) or from point to point to be positioned (e.g. *semi-kinematic* or *rapid static*), and whose measurements are combined with those from a *monitor* receiver for *relative positioning* (also referred to as a *remote*)

satellite constellation the complete set of satellites and their configuration in space

satellite message the package of information modulated on both the L1 and L2 *carrier frequencies* which includes among other information, the *broadcast ephemerides* and satellite health status

selective availability (SA) a technique which is used to limit real-time accuracy achievable by civilian users and which consists of degradation of the broadcast orbit (i.e. the satellites' "known" position in space) and dithering of the satellite clocks

semi-kinematic a *relative positioning* method in which the *rover* receiver remains stationary on each point for several seconds, and maintains lock on satellites while moving between points (also referred to as *stop and go*)

site a term often used to refer to a point on the earth's surface at which GPS observations are collected (also referred to as *station*)

single point positioning the determination of the coordinates of a receiver with respect to the earth's reference frame by intersection of the signals from four or more satellites (also referred to as *absolute positioning* or simply *point positioning*)

standard deviation a measure of the dispersion of observations about the mean, sometimes limited to apply only to *normal distributions*, but more commonly used to refer to any distribution, in which case it is the same as *root mean square*

static refers to the type of positioning where a GPS receiver is stationary while data is collected

station a term often used to refer to a point on the earth's surface at which GPS observations are collected (also referred to as *site*)

stop and go a relative positioning method in which the rover receiver remains stationary on each point for several seconds and maintains lock on satellites while moving between points (also referred to as *semi-kinematic*)

systematic errors those errors which have some known pattern or behaviour which biases the observations

troposphere the layer of the atmosphere up to 80 km above the earth

tropospheric errors the delay of GPS signals due to transmission through the *troposphere*

user equivalent range error (UERE) the contribution of all errors to *single point positioning* accuracy

user segment includes all those who use GPS tracking equipment to receive GPS signals to satisfy specific positioning requirements

window the periods during the 24 hour day when there are a sufficient number of satellites in view to meet the positioning requirement

Y code the encrypted GPS code which replaces the P code when anti-spoofing is implemented

APPENDIX B

GPS SATELLITE INFORMATION SOURCES

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GPS SATELLITE INFORMATION SOURCES

GPS SATELLITE INFORMATION SOURCES

(i) GPS Information Center

The Global Positioning System Information Center (GPSIC) provides civilian users of the NAVSTAR GPS with system status and other information. The GPSIC is operated by the U.S. Coast Guard. It receives GPS status messages from the U.S. Air Force, which has operational control of the system, and gives the information wide dissemination. Although the information is only updated during the GPSIC's working hours, advisory services are accessible 24 hours a day, seven days a week.

The information available consists of current constellation status (satellites healthy/unhealthy), recent outages, future scheduled outages, current orbital descriptions (almanac data) suitable for making GPS coverage and satellite visibility predictions, and precise orbital ephemerides computed by the U.S. National Geodetic Survey (NGS).

A brief summary of the constellation status is available on voice recording at (703) 313-5907. More detailed information is available through a computer bulletin board. Anyone can use this bulletin board at no charge. Registration is done on-line on the first session. The bulletin board may be accessed at (703) 313-5910 for modem connections at 300 to 14400 bps. Comms parameters are: 8 data bits, 1 stop bit and no parity.

For additional information on the centre or the bulletin board write to the Commanding Officer, U.S. Coast Guard, Omega Navigation System Center, 7323 Telegraph Road, Alexandria, VA 22310-3998, U.S.A. or call (703) 313-5900.

(ii) Naval Observatory GPS Bulletin Board

Operated by the U.S. Air Force Naval Observatory in Washington, D.C., this bulletin board offers clock data and general GPS information, including constellation status, electronic mail, downloadable files and user advisories.

The bulletin board can be accessed at either (202) 653-0155 or (202) 653-0068. The comms parameters are: no parity, 8 data bits and 1 stop bit. The password "CESIUM133" must be used to access the system and continue with on-line registration. Further information or assistance is available at (202) 653-1525 or at (202) 653-1034.

(iii) Holloman GPS Bulletin Board Service

Operated by the U.S. Air Force at Holloman Air Force Base, New Mexico, this bulletin board offers GPS information including constellation status, almanac data, electronic mail, downloadable files, and user advisories.

The bulletin board can be accessed at (505) 679-1525. The system uses a "smart" modem and will automatically adjust for protocols. For further information or assistance contact (505) 679-1657 or (505) 679-1787.

POST COMPUTED EPHEMERIDES

The Geodetic Survey Division calculates and archives precise ephemerides for the GPS satellite constellation as part of its Active Control System (ACS). (See Appendix G.) The ephemerides are computed from data collected at 7 Canadian stations augmented by up to 12 globally distributed core stations of the International GPS Geodynamics Service (IGS). Ephemeris data are computed in the International Earth Rotation Service (IERS) Terrestrial Reference Frame of 1991 (ITRF91), which agrees with NAD83 (or WGS84) within 0.2 parts per million.

Precise ephemerides are provided as daily files (0:00 to 23:45 GPS Time). They are available typically within a week following the observations. The precise GPS satellite ephemerides can be obtained from GSD as follows (some charges may apply):

1) Through the Canadian Geodetic Bulletin Board Service (CGBBS): Users can access ephemerides data through the CGBBS via dial-up modem and datapac, or through a series of connection services on the Internet
2) On PC compatible $3^1/_2$ inch (1.44 Mb) diskettes

Requests for information should be directed to:

Geomatics Canada
Geodetic Survey Division
Information Services
615 Booth Street
Ottawa, Ontario K1A 0E9
(613) 995-4410 or (613) 992-2061
Fax: (613) 995-3215
E-mail: information@geod.nrcan.gc.ca

Precise orbital ephemerides are also available from the U.S. National Geodetic Survey. These are based on computations of tracking data collected from stations of the Cooperative International GPS Tracking Network (CIGNET). Satellite orbital data are available two weeks after the tracking data are collected on the GPS Information Center's bulletin board (access procedures provided earlier in this appendix).

If the user requires orbits for weeks no longer posted on the GPSIC bulletin board, the orbits may be obtained on high density floppy disks for a fee, by contacting the NGS Information Center at:

National Geodetic Information Center
NOAA, NGS N/CG174
SSMC3 Stn 9202
1315 East West Highway
Silver Spring MD, 20910 USA
Phone: (301) 713-3242

[illegible]

[illegible]

POST-PROCESSED GPS EPHEMERIDES

The Geodetic Survey Division calculates and archives precise ephemerides for the GPS satellite constellation as part of its Active Control System (ACS). (See Appendix G). The ephemerides are computed from data collected at 7 Canadian stations augmented by up to 12 globally distributed core stations of the International GPS Geodynamics Service (IGS). Ephemeris data are computed in the International Earth Rotation Service (IERS) Terrestrial Reference Frame of 1991 (ITRF91), which agrees with NAD83 (or WGS84) within 0.2 parts per million.

Precise ephemerides are provided as daily files (0:00 to 23:45 GPS Time). They are available typically within a week following the observations. The precise GPS satellite ephemerides can be obtained from GSD as follows (some charges may apply):

a) Through the Canadian Geodetic Bulletin Board Service (CGBBS) – Users can access ephemerides data through the CGBBS via dial-up modem and datapac or through a series of connection services on the Internet.
b) On PC compatible 3½ inch (1.44 MB) diskettes.

Requests for information should be directed to:

Geomatics Canada
Geodetic Survey Division
Information Services
615 Booth Street
Ottawa, Ontario K1A 0E9
(613) 995-4410 or (613) 992-2061
Fax: (613) 995-3215
E-mail: information@geod.emr.ca

Precise orbital ephemerides are also available from the U.S. National Geodetic Survey. These are based on computations of tracking data collected from stations of the Cooperative International GPS Tracking Network (CIGNET). Satellite orbital data are available two weeks after the tracking data are collected on the GPS Information Center's Bulletin Board (access procedures provided earlier in this Appendix.

APPENDIX C

GEOMAGNETIC ACTIVITY ZONES AND INFORMATION SOURCES

GEOMAGNETIC ACTIVITY ZONES AND INFORMATION SOURCES

Geomagnetic Activity Zones

The behaviour of the ionosphere is a function of many interrelated variables including the solar cycle, time of year, time of day, geographical location and geomagnetic activity.

The Geophysics Division of the Geological Survey Sector at EMR monitors geomagnetic activities across the country and has determined three zones in Canada according to the average level of activity (see Figure C.1). In the sub-auroral zone (Canadian southern latitudes), the magnetic flux is usually small and steady, leading to a generally homogeneous and predictable ionosphere. In the auroral and polar zones (latitudes of ≈55° and higher), the magnetic flux is large and irregular leading to a generally disturbed ionosphere. The zone boundaries are not absolute and vary with seasons, solar cycles, sunspot activities, etc.. It should also be kept in mind that at all Canadian latitudes there is potential for sudden disturbances in the earth's magnetic field (magnetic storms) causing large disturbances in the ionosphere.

GEOMAGNETIC ACTIVITY PREDICTION

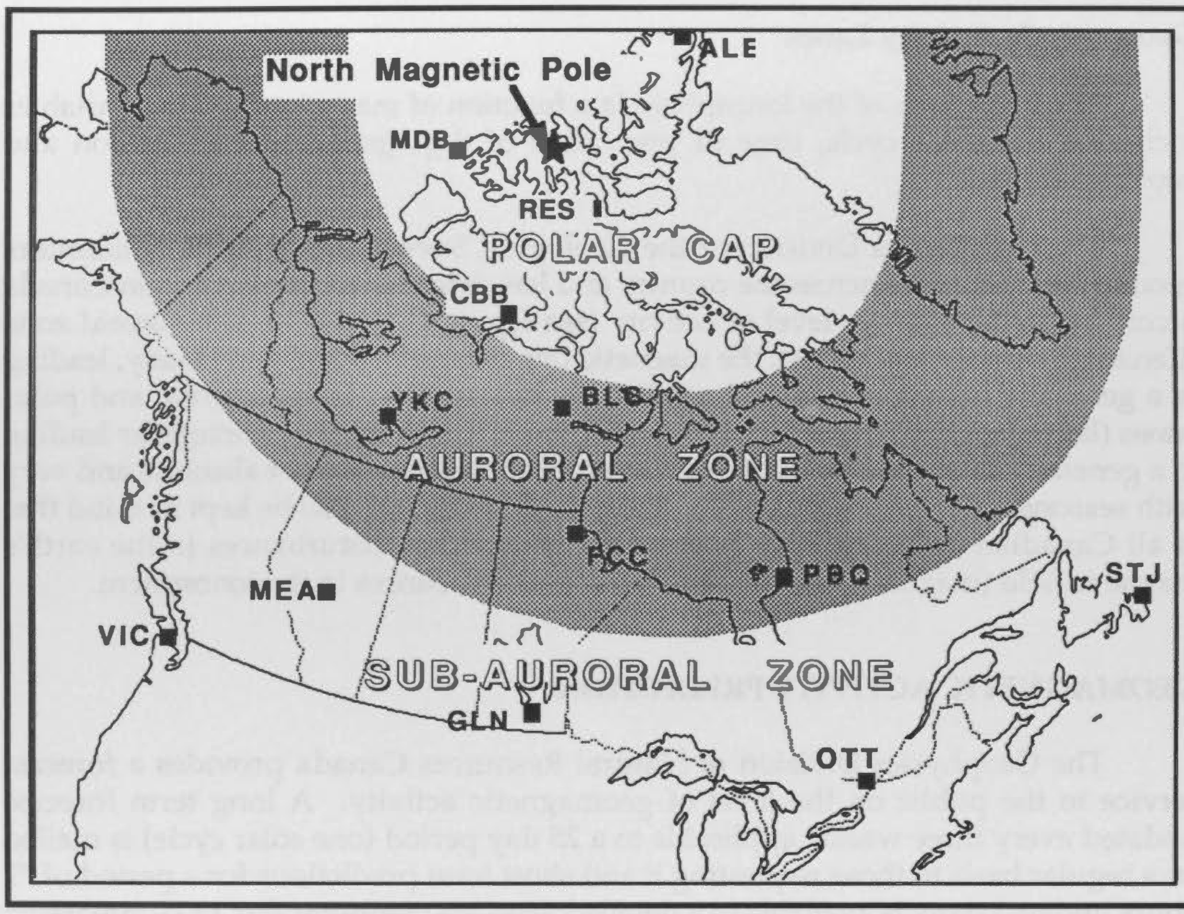
The Geophysics Division of Natural Resources Canada provides a forecast service to the public on the level of geomagnetic activity. A long term forecast updated every three weeks, applicable to a 28 day period (one solar cycle) is mailed on a regular basis to those requesting it and short term predictions for a period of 72 hours updated daily is available in a detailed form via computer link or summarized on a voice recorded message. GPS users are encouraged to consult these forecasts before and during their campaigns.

The voice recorded forecast (72 hours) is available at (613) 992-1299.

To be included in the mailing of the long term forecast or to access the detailed short term forecast contact the Chief Geomagnetic Forecaster at (613) 837-3527 or in writing:

Geomagnetic Forecasting Service
Geophysics Division
1 Observatory Crescent
Ottawa, Ontario K1A 0Y9

It is also possible to receive actual geomagnetic data collected at individual monitoring sites. This information is sometimes useful to corroborate that problem data are caused by high ionospheric activity. Instructions on how to access this information can be obtained at the address above.



Canadian Magnetic Observatory Network					
Polar Cap		Auroral Zone		Sub-Auroral Zone	
ALE	Alert	CBB	Cambridge Bay	MEA	Meanook
RES	Resolute Bay	BLC	Baker Lake	GLN	Glenlea
MDB	Mould Bay	YKC	Yellowknife	STJ	St. John's
		FCC	Fort Churchill	VIC	Victoria
		PBQ	Poste de la Baleine	OTT	Ottawa

Figure C.1. Geomagnetic Activity Zones in Canada

APPENDIX D

HORIZONTAL AND VERTICAL CONTROL INFORMATION SOURCES

		Canadian Magnetic Observatory Network			
Polar Cap		Auroral Zone		Sub Auroral Zone	
[illegible]	[illegible]	CBB	Cambridge Bay	MEA	Meanook
[illegible]	Resolute Bay	BLC	Baker Lake	GLN	Glenlea
[illegible]	[illegible]	YKC	Yellowknife	STJ	St. John's
		FCC	Fort Churchill	VIC	Victoria
		PBQ	Poste de la Baleine	OTT	Ottawa

Figure C.1. Geomagnetic Activity Zones in Canada

HORIZONTAL AND VERTICAL CONTROL INFORMATION SOURCES

The Geodetic Survey Division maintains a National Geodetic Database (NGDB) comprised of descriptions and coordinates for all horizontal and vertical control across the country which falls under its jurisdiction. Information from the NGDB is made available on a cost recovery basis.

For further information contact:

Geodetic Survey Division
Information Services
615 Booth Street
Ottawa, Ontario K1A 0E9
(613) 995-4410 or (613) 992-2061
Fax: (613) 995-3215
E-mail: information@geod.nrcan.gc.ca

APPENDIX E

GEOID INFORMATION SOURCES

GEOID INFORMATION SOURCES

The Geodetic Survey Division has produced three tables representing geoid undulation (N) values, and the deflection of the vertical for the north-south (ξ) and east-west (η) components for Canada. These tables are derived from the Canadian geoid model GSD91 (Véronneau and Mainville, 1992). The geoid undulation table is recommended for use with GPS satellite-derived coordinate values and is also recommended for use with the NAD83 coordinate values.

The three tables (N, ξ and η) cover most of the Canadian territory. They extend to the offshore areas between 46° and 142° west longitude and from 41° to 72° north latitude. Tabular values are given at intervals of 5 arc minutes in latitude and longitude. A quadratic interpolation method should be used to interpolate the table. The files of geoid heights (N) and deflections of the vertical (ξ, η), as well as quadratic interpolating software, are available on IBM compatible, Macintosh, VAX and UNIX computers. These products are distributed by the Geodetic Survey Division on a cost recovery basis. For information please contact:

Geodetic Survey Division
Information Services
615 Booth Street
Ottawa, Ontario K1A 0E9
(613) 995-4410 or (613) 992-2061
Fax: (613) 995-3215
E-mail: information@geod.nrcan.gc.ca

For further details concerning the accuracy of geoid models, or to obtain geoid values outside Canada or for any additional information, please contact Marc Véronneau at (613) 995-4345 or André Mainville at (613) 995-4504.

Reference

Véronneau, M. and A. Mainville (1992): "Computation of a Canadian Geoid Model Using FFT Technique to Evaluate Stokes' and Vening-Meinesz' Formulas in a Planar Approximation", Internal Report, Geodetic Survey Division, Canada Centre for Surveying, Department of Energy, Mines and Resources, Ottawa.

GEOID INFORMATION SOURCES

The Geodetic Survey Division has produced three tables representing geoid undulation (N) values, and the deflection of the vertical for the north-south (ξ) and east-west (η) components for Canada. These tables are derived from the Canadian geoid model GSD91 (Véronneau and Mainville, 1992). The geoid undulation table is recommended for use with GPS satellite-derived coordinate values and is also recommended for use with the NAD83 coordinate values.

The three tables (N, ξ and η) cover most of the Canadian territory. They extend to the offshore areas between 49° and 142° west longitude and from 41° to 72° north latitude. Tabular values are given at intervals of 5 arc minutes in latitude and longitude. A quadratic interpolation method should be used to interpolate the table. The files of geoid heights (N) and deflections of the vertical (ξ, η), as well as quadratic interpolating software, are available on IBM compatible, Macintosh, VAX and UNIX computers. These products are distributed by the Geodetic Survey Division on a cost recovery basis. For information please contact:

Geodetic Survey Division
Information Services
615 Booth Street
Ottawa, Ontario K1A 0E9
(613) 995-4410 or (613) 995-3263
Fax: (613) 995-3215
E-mail: Information@geod.emr.ca

For further details concerning the accuracy of geoid models, or to obtain geoid values outside Canada or for any additional information, please contact Marc Véronneau at (613) 995-4368 or André Mainville at (613) 995-4504.

Reference

Véronneau, M. and A. Mainville (1992): "Computation of a Canadian Geoid Model Using FFT Technique to Evaluate Stokes' and Vening Meinesz' Formulas in a Planar Approximation". Internal Report, Geodetic Survey Division, Canada Centre for Surveying, Department of Energy, Mines and Resources, Ottawa.

APPENDIX F

SAMPLE GPS LOG FORMS

GPS FIELD LOG

Page 1 of __

Project Name ____________ *Project Number* ____________

Receiver Model/No ____________
Receiver Software Version ____________
Data Logger Type/No ____________
Antenna Model/No ____________
Cable Length ____________
Ground Plane Extensions Yes ( ) No ( )

Station Name ____________
Station Number ____________
4-Char ID ____________
Date ____________
Obs. Session ____________
Operator ____________

Data Collection

Collection Rate ____________
Start Day/Time ____________
End Day/Time ____________

Receiver Position

Latitude ____________
Longitude ____________
Height ____________

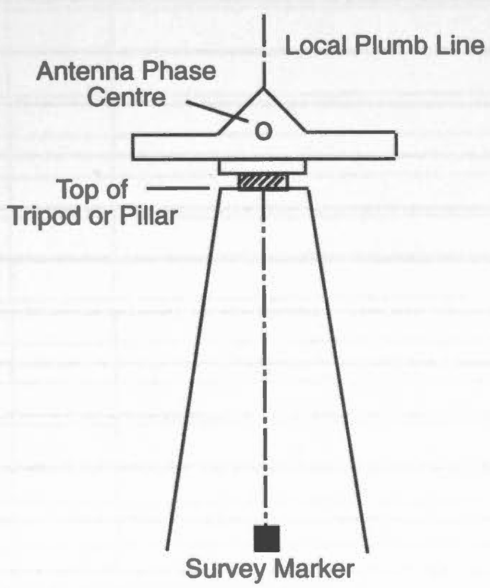
Obstruction or possible Interference sources ____________

General weather conditions ____________

Detailed meteorological observations recorded: Yes ( ) No ( )

Antenna Height Measurement

Show on sketch measurements taken to derive the antenna height. If slant measurements are taken, make measurement on two opposite sides of the antenna. Make measurements before and after observing session.



Vertical measurements ( )

Slant measurements ( ): radius ____ m

BEFORE	AFTER
____m____in	____m____in
____m____in	____m____in

Mean ____________

Corrected to vertical if slant measurement ____________

Vertical offset to phase centre ____________

Other offset (indicate on sketch) ____________

TOTAL HEIGHT ____________

Verified by: ____________

GPS FIELD LOG Page of

Station Name ______________ Station Number ______________ Date ________

Meteorlogical Data

Met Sensor No. ______________ Barometer No. ______________

Relative Humidity Reported instead of Wet Temperature ( )

Time												
Dry Temp (°C)												
Wet Temp (°C) or Rh (%)												
Barometer Reading (mb)												
Barometer correction												
Pressure (mb)												

General observations

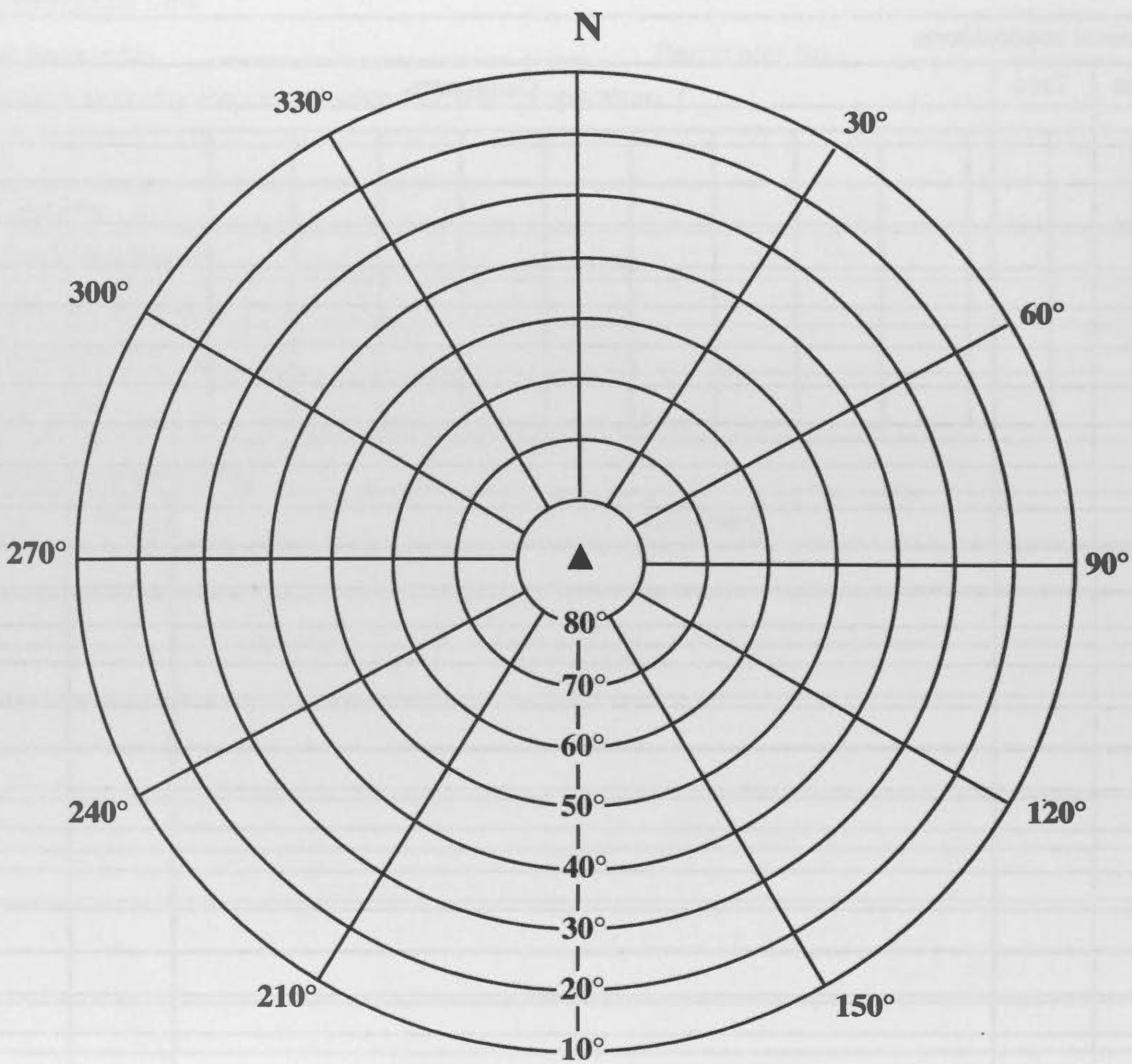
Day	Time	Comments

GPS FIELD LOG Page of

Station Name ____________ Station Number ____________ Date ________

General observations		
Date	Time	Comments

GPS STATION OBSTRUCTION DIAGRAM



Identify obstructions and their elevation angle as seen from the station mark.

Indicate the distance to ant metallic structure or reflective surface.

Magnetic Declination ____________

Declination applied to this figure? Yes ( )
No ( )

Height above marker that horizon was mapped from: ____________

Station Name ____________ **Date** ____________

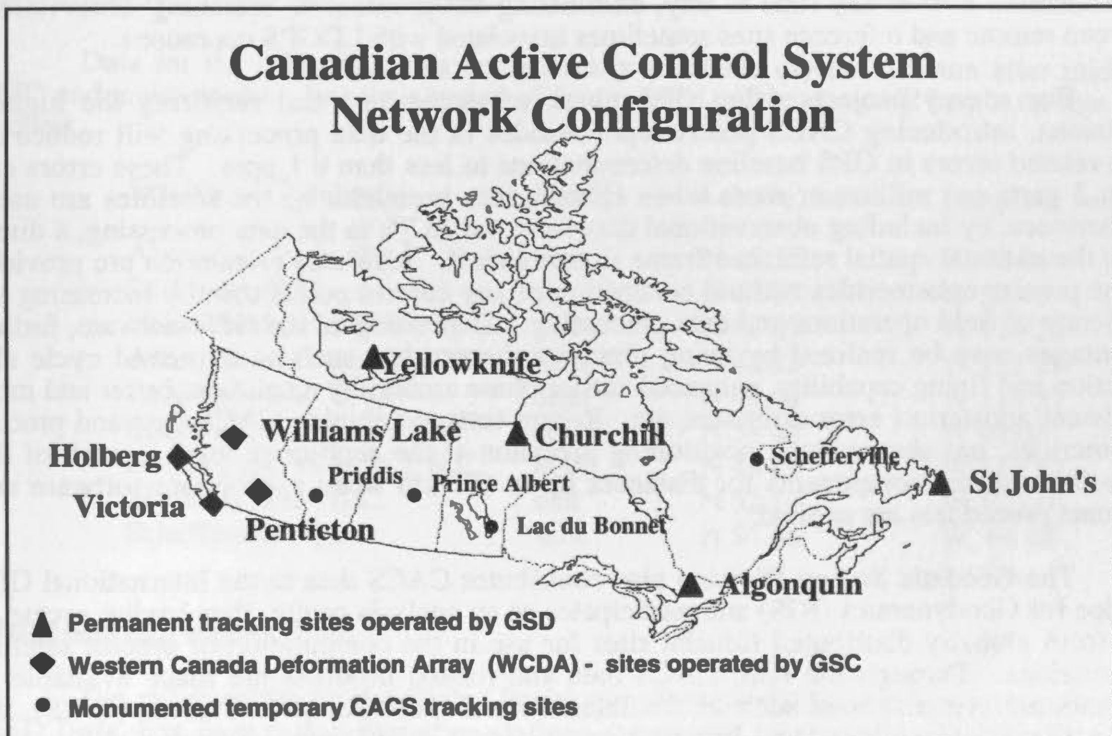
Station Number ____________ **Operator** ____________

APPENDIX G

THE CANADIAN ACTIVE CONTROL SYSTEM

THE CANADIAN ACTIVE CONTROL SYSTEM

The Geodetic Survey Division of Geomatics Canada, in partnership with Geological Survey of Canada, is presently operating the Canadian Active Control System (CACS) to provide improved GPS positioning capability for the Canadian surveying and geophysical community as well as for other spatial referencing needs. The CACS provides efficient access to modern spatial reference frames (NAD83, ITRF, etc.) and improves effectiveness and accuracy of GPS applications. This is accomplished by monitoring GPS integrity and performance from the analysis of data acquired through continuous tracking; by computing and making available precise satellite ephemerides (GPS orbits) and precise satellite clock corrections; by supporting Wide Area Differential GPS (WADGPS) development and other applications (geodynamics, precise time transfer, etc.).



The system is supported by unattended tracking stations, referred to as Active Control Points (ACPs), which continuously record carrier phase and pseudorange measurements for all satellites of the Global Positioning System (GPS) within station view. Presently, ACPs are located in Algonquin Park, Ont., Yellowknife, N.W.T., Penticton, Victoria, Williams Lake and Holberg, B.C., St. John's, Nfld., Schefferville, Qué., and Churchill, Man. Each ACP is equipped with a high precision dual-frequency GPS receiver and an atomic frequency standard. Temperature, pressure and humidity data are also collected at selected ACP sites. The data collected at each ACP is retrieved on a daily basis by a central processing facility in Ottawa.

The availability of precise ephemerides, precise satellite clock corrections and observational data from the ACPs offers significant benefits for Canadian users carrying out GPS surveys. These CACS products make it possible to position any point in Canada with a precision ranging from a centimetre to a few metres in relation to the national spatial reference frame without actually occupying an existing control monument or base station.

Positioning at the metre level from pseudo-range (code) observations without the use of a base station is made possible by using CACS precise satellite clock corrections. These corrections account for the dithering introduced by selective availability (SA), which is the main source of error in GPS code positioning. They can be applied anywhere in Canada to correct the users observed ranges and, when used along with CACS precise ephemerides, provide positioning accuracies in the 1 to 10 metre range depending on the user's receiver measurement noise and multipath. The advantage of using satellite clock corrections is that some of the station-specific errors can be accounted for directly, as opposed to assuming commonality of errors between base station and remote site as with local DGPS. Since the satellite corrections are based on a network of accurately known reference points, some of the uncertainty associated with using control data from a single base station is effectively removed. The distributed stations of the CACS also ensures common satellite visibility for any Canadian user at any time of day, eliminating the problem of 'matching' observations between remote and reference sites sometimes associated with LDGPS operations.

For survey projects using GPS phase measurements and requiring the highest precisions, introducing CACS precise ephemerides in the data processing will reduce all orbit-related errors in GPS baseline determinations to less than 0.1 ppm. These errors can reach 3 parts per million or more when ephemerides broadcast by the satellites are used. Furthermore, by including observational data from the ACPs in the data processing, a direct tie to the national spatial reference frame is established. Scale and orientation are provided by the precise ephemerides without occupation of any control points thereby increasing the efficiency of field operations and data processing. Depending on the GPS software, further advantages may be realized by using precise ephemerides, such as improved cycle slip detection and fixing capability, enhanced carrier phase ambiguity resolution, better and more consistent aposteriori error estimates, etc. Recent tests, combining CACS data and precise ephemerides, has shown static positioning precision at the centimetre level in each of the three-dimensional components for distances up to 600 km when appropriate software and adequate procedures are applied.

The Geodetic Survey Division also contributes CACS data to the International GPS Service for Geodynamics (IGS) and participates as an analysis centre, thus having access to data from globally distributed fiducial sites for use in the computation of precise satellite ephemerides. Through the IGS, CACS data and related products are made available to international organizations such as the International Earth Rotation Service (IERS), the NASA Crustal Dynamics Data Information System (CDDIS), the US National Geodetic Survey (USNGS), the US Naval Observatory (USNO) and other organizations interested in Earth dynamics. The precise observations of the satellites made from the fiducial stations are used to establish the Earth Orientation Parameters (EOP) and derive inter-station baseline lengths and orientation for regional monitoring stations. Changes in baseline components over time provide quantitative data for studies of geodynamics, natural hazards and global change.

There are presently seven international analysis centres contributing to the IGS. Recently the Geodetic Survey Division has assumed, at the request of the IGS Governing Board, the responsibility of coordinating its analysis centres. This responsibility includes generation of combined precise ephemerides and other products from data submitted by the seven centres.

PRODUCTS AVAILABLE

The CACS observational data, precise GPS satellite ephemerides and precise satellite clock corrections are available electronically from the Geodetic Survey Division BBS service accessible via modem, INTERNET, and Datapac or by mail on 3 1/2 inch (1.44 Mb) diskettes.

CACS observational data

CACS observational data consist of dual-frequency calibrated satellite code and carrier phase observations from continuous tracking of up to eight satellites at 30-second intervals. Data are archived daily in the RINEX format (version 2). Station files contain data collected over a 24-hour period (0:00:00 to 23:59:30 GPS Time). Each 1-day file contains approximately 2 Mb of data per station.

Data for the following sites are generally available on-line 6 hours after midnight (UT) and maintained on-line for a period of four months. Older data will be put on-line upon request.

Site Name (location)	Site ID	Lat (deg. min.)	Long (deg. min.)
Algonquin Park, Ont.	algo	N 45 57	W 78 04
St. John's, Nfld.	stjo	N 45 35	W 52 41
Yellowknife, NWT	yell	N 62 29	W 114 29
Albert Head (Victoria), B.C.	albh	N 48 23	W 123 29
Penticton, B.C.	drao	N 49 19	W 119 37
Churchill, Man.	chur	N 58 45	W 94 05
Holberg (N. Vanc. Is.), B.C.	holb	N 49 19	W 119 37
Williams Lake, B.C.	will	N 52 14	W 122 10
Schefferville, Qué.	sche	N 54 48	W 66 48

Precise ephemerides

The ephemerides for the Global Positioning System (GPS) satellites are computed at GSD from data collected at Canadian stations augmented by up to 22 globally distributed core stations of the International GPS Service for Geodynamics (IGS). Ephemeris data are computed in the International Earth Rotation Service (IERS) Terrestrial Reference Frame (ITRF), which is fully compatible with WGS 84 and agrees with NAD 83 within 0.2 parts per million. Based on IGS orbit comparisons, the CACS precise ephemerides are determined to better than 20 centimetres (one sigma) in each coordinate.

Precise ephemerides are provided as daily files (0:00 to 23:45 GPS Time) and are available typically within 2 to 5 days following the observations. They are presently distributed in the internationally accepted NGS-SP3 format which contains all satellites' X, Y, Z positions and clock information at 15-minute intervals.

Precise satellite clock corrections

Precise offsets between individual satellite clocks and the CACS reference clock are computed for satellite arcs visible in Canada based on the precise ephemerides and observational data from CACS stations. These precise satellite clock corrections account for the dithering effect introduced by selective availability (SA). Although the clock corrections are archived at 30-second intervals, preliminary tests indicate no appreciable degradation in the positioning accuracy when they are interpolated for higher data rates (e.g. 1-sec. data). Software GPSPACE* (see description below) can be used to apply these satellite clock corrections to obtain improved positioning accuracy. Precise satellite clock corrections are also computed for global coverage upon request.

Precise clock corrections are archived in ASCII format. Each file contains the clock corrections for each individual satellite for a 24-hour period (0:00:00 to 23:59:30 GPS Time) at 30-second intervals. They are typically available on-line within a week following the observation.

Software

EPH_UTIL: This Software includes two PC-compatible utility programs for the manipulation of the precise ephemeris files: ORBINT for the interpolation of the ephemerides to user-specified epochs or conversion from SP3 to other formats (SP1, SP3 with or without satellite velocities) and ORBMRG for merging up to 7 daily ephemeris files into a single file.

GPSPACE: GPSPACE (GPS Positioning from ACS Clocks and Ephemerides) is a GPS positioning program for post-processing static or kinematic pseudo-range (code) data. It applies precise satellite clock information computed from the CACS to improve the accuracy of the user's observed ranges. The clock corrections are applicable anywhere in Canada (and in any geographical area worldwide upon request), and when used in conjunction with CACS precise ephemerides, provide positioning accuracies in the 1 to 10 metre range (RMS) depending on the user's receiver measurement noise and multipath. GPSPACE uses RINEX observation and ephemeris files and processes data sequentially in time, estimating independent positions for every epoch where 4 or more satellites are available. It allows for input of precise ephemeris information in the SP3 format as well as broadcast ephemerides.

PRODUCT DISTRIBUTION

Access to CACS Data Through the Information Services Unit: Requests for CACS products provided on magnetic medium should be directed to Information Services at the Geodetic Survey Division (see address below).

Access to CACS Data Through the Canadian Geodetic Bulletin Board Service (CGBBS): Users can access CACS data through the CGBBS via dial-up modem and datapac, or through a series of connection services on the Internet.

Users will be charged a subscription fee for access to the CGBBS and for CACS data downloaded. For additional information or for access to the CGBBS, please contact the Information Services Unit at the address below.

CACS Observational Data:	31/2 in. (1.44 Mb) diskette (accommodates 2 days of data from one site in a compressed format).
Precise Ephemerides:	31/2 in. (1.44 Mb) diskette (accommodates 7 days of data for all satellites).
Precise Satellite Clock Corrections:	31/2 in. (1.44 Mb) diskette (accommodates 3 days of data for all satellites).
EPH_UTIL:	31/2 in. (1.44 Mb) diskette (software and documentation).
GPSPACE	31/2 in. (1.44 Mb) diskette (software, documentation and a sample data set).

Requests for information on Geodetic products and services should be directed to:

Information Services
Geodetic Survey Division
615 Booth Street
Ottawa, Ontario
K1A 0E9

Tel: (613) 995-4410
Fax: (613) 995-3215
Internet: information@geod.nrcan.gc.ca

NOTICE - **Data or software distributed by Geodetic Survey Division is subject to the following terms:**

1. The User acknowledges that the Data or Software, which has been prepared or published by Her Majesty acting through the Department of Natural Resources Canada (NRCan), is protected under the *Copyright Act* and belongs to Her Majesty.
2. The User shall not sell, loan, transfer or license the Data or Software, or otherwise assign any rights under this Agreement to any third party without the prior written permission of NRCan.
3. If the User wishes to produce a product for retailing or other purposes using the Data or Software supplied by Her Majesty, a licensing agreement will be required and may be negotiated with NRCan to authorize the development and/or sale of such a product.
4. The Data or Software is provided on an "as is" basis and Her Majesty makes no guarantees, representations or warranties respecting the Data or Software, either expressed or implied, arising by law or otherwise, including but not limited to, effectiveness, completeness, accuracy or fitness for a particular purpose.
5. Her Majesty shall not be liable in respect of any claim, demand or action, irrespective of the nature of the cause of the claim, demand or action alleging any loss, injury or damages, direct or indirect, which may result from the User's use of the Data or Software, or in any way relating to this Agreement. Her Majesty shall not be liable in any way for loss of profits or contracts, or any other consequential loss of any kind resulting from any defect in the Data or Software.

APPENDIX H

SUGGESTED READING FOR GENERAL GPS INFORMATION

SUGGESTED READING FOR GENERAL GPS INFORMATION

Reference:	Available From:
GPS World (magazine)	GPS World Box 1965 Marion, OH 43305-2064 U.S.A. (614) 382-0886
Guidelines and Specifications for GPS Surveys (1992)	Geomatics Canada Geodetic Survey Division Information Services 615 Booth Street Ottawa, Ontario K1A 0E9 (613) 995-4410 or (613) 992-2061 Fax: (613) 995-3215 E-mail: information@geod.emr.ca
Guide to GPS Positioning (1987) by D. Wells et al.	The Canadian Institute of Geomatics Box 5378 Postal Station F Ottawa, Ontario K2C 3J1 (613) 224-9851
Getting Started With GPS Surveying (1992) by S. McElroy, published by the The Global Positioning System Consortium	GPSCO C/O GPSCO Steering Committee Secretariat Land Information Centre Box 143 Bathurst NSW 2795 Australia (063) 328-200 FAX: (063) 318-095