PART V: THE GLOBAL POSITIONING SYSTEM

5.1 Background

The Global Positioning System (GPS) is a satellite based, passive, three dimensional navigational system operated and maintained by the Department of Defense (DOD) having the primary purpose of supporting tactical and strategic military operations. Like many systems initially designed for military purposes, GPS has been found to be an indispensable tool for many civilian applications, not the least of which are surveying and mapping uses.

There are currently three general modes that GPS users have adopted: absolute, differential and relative. Absolute GPS can best be described by a single user occupying a single point with a single receiver. Typically a lower grade receiver using only the coarse acquisition code generated by the satellites is used and errors can approach the 100m range. While absolute GPS will not support typical MDOT survey requirements it may be very useful in reconnaissance work.

Differential GPS or DGPS employs a base receiver transmitting differential corrections to a roving receiver. It, too, only makes use of the coarse acquisition code. Accuracies are typically in the sub-meter range. DGPS may be of use in certain mapping applications such as topographic or hydrographic surveys. DGPS should not be confused with Real Time Kinematic or RTK GPS surveying.

Relative GPS surveying employs multiple receivers simultaneously observing multiple points and makes use of carrier phase measurements. Relative positioning is less concerned with the absolute positions of the occupied points than with the relative vector (dX, dY, dZ) between them.

5.2 GPS Segments

The Global Positioning System is made of three segments: the Space Segment, the Control Segment and the User Segment.

5.2.1 The Space Segment

The space segment consists of 24 satellites or SV’s. The SV’s are in six orbital planes inclined 55^0 to the equator at an altitude of about 21,000 kilometers above the surface of the earth. The orbital period is approximately 11 hours and 56 minutes.

5.2.2 The Control Segment

The control segment consists of a master control station and five monitoring stations. The Master Control Station (MCS) is located at Schriever Air Force Base, Colorado Springs, Colorado. The MCS computes updates for the navigation message (broadcast ephemeris and SV clock corrections), uses information from monitoring stations to compute the precise ephemeris and initiates SV repositioning and replacement as necessary. [1]

Monitoring Stations are at Ascension Island, Colorado Springs, Diego Garcia, Hawaii and Kwajelein. Monitoring Stations observe P-Code pseudoranges and integrated Doppler measurements from all available SV's, compare actual SV positions with latest reference ephemeris and determine differences and calculate new SV positions. [2]

5.2.3 The User Segment

The user segment consists of those who employ the GPS system in any civilian or military application.

5.3 GPS Reference Systems

There are three coordinate reference systems that the typical MDOT surveyor should be familiar with: the Geodetic Coordinate System (ellipsoidal), the Geocentric Coordinate System (Cartesian rectangular) and the Local Space Rectangular Coordinate System (topocentric). It should be understood by the MDOT surveyor that while the latter two systems are Cartesian systems, they should not be confused with the Michigan State Plane Coordinate System (MSPCS). MSPCS is described in **Part IV** of this manual.

5.3.1 Geodetic Coordinate System

The Geodetic Coordinate System is a three dimensional curvilinear system based upon the ellipsoid. Its components are longitude (λ), latitude (φ) and height (h).

Longitude is the angle formed at the center of the ellipsoid on the equatorial plane from the Greenwich meridian to the meridian of the point of interest. Longitude may be expressed in an easterly direction from 0^0 at the Greenwich meridian to 360^0. Longitude may also be expressed in a westerly direction from the Greenwich meridian to 180^0. West longitude is used for MDOT projects.

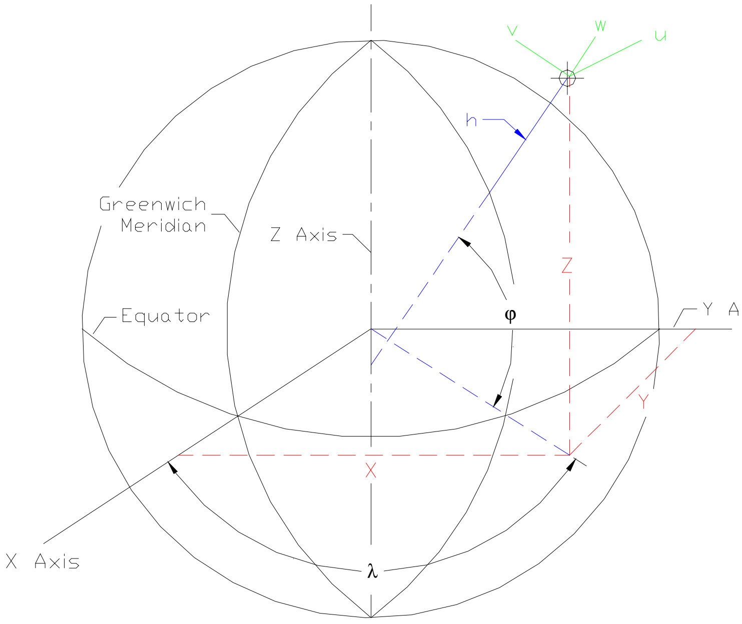
Latitude is the angle formed at the intersection of a line normal to the ellipsoid on the meridian of the point of interest with the equatorial plane. 0^0 is along the equatorial plane and latitude measured positive north of the equator and negative south of the equator. Maximum value of latitude is $\pm 90^0$. North latitude is used for MDOT projects.

Height (h) is the linear distance measured along the line normal to the ellipsoid from the surface of the ellipsoid to the point of interest. This value is commonly referred to as ellipsoid height.

5.3.2 Geocentric Coordinate System

The Geocentric Coordinate System is a three dimensional Cartesian coordinate system whose point of origin is the center of the earth. Its Z axis coincides with the polar axis. Its X axis lies in the equatorial plane from the center of the earth through the intersection of the Greenwich Meridian with the equatorial plane. The Y axis is normal with the X axis such that a right handed coordinate system is formed. This system is referred to as the X,Y,Z, system.

Figure 5.1
Coordinate Reference Systems



5.3.3 Local Space Rectangular Coordinate System

The Local Space Rectangular Coordinate System is a three dimensional Cartesian coordinate system having as its origin a point on or near the surface of the earth.[3] The W axis is the line normal to the ellipsoid at the point of origin. The V axis is perpendicular to the U axis and to the meridian plane. The U axis forms a right handed coordinate system with W and V. This system is commonly referred to as the U,V,W system. Some GPS receivers may report this system as the E,N,U system for Easting, Northing, Upper.

Transformation algorithms from one system to either of the others may be found in **Appendix H** to this manual. The later two systems should not be confused with the Michigan State Plane Coordinate System (MSPCS) which is described in **Part IV** of this manual.

5.3.4 Reference Ellipsoids

The Global Positioning System is referenced to the World Geodetic System of 1984 (WGS-84) which defines the semi-major axis of the ellipsoid (a) as 6,378,137 meters and flattening (f) as 1/298.257223563. These parameters define a best fit figure for the size and shape of the earth. MSPCS is referenced to the North American Datum of 1983 (NAD-83(19XX)) which is based upon the Geodetic Reference System of 1980 (GRS-80). GRS-80 ellipsoid parameters are a semi-major axis (a) of 6,378,137 meters (identical to WGS-84) with a flattening (f) of 1/298.25722201.

5.4 GPS Signals

The fundamental frequency used in GPS is 10.23 MHz. Multiplying 10.23 by 154 yields the L1 carrier frequency of 1575.24 MHz having a wavelength of about 19 cm. Multiplying 10.23 by 120 yields the L2 carrier frequency of 1227.60 MHz having a wavelength of about 24 cm.

Impressed upon the L1 and L2 carrier waves are pseudo random noise (PRN) codes. The L1 frequency carries the Precise Code and the Coarse Acquisition Code. The L2 frequency carries the Precise Code only.

The Coarse Acquisition Code or C/A code has an effective wavelength of about 300 meters and is available to any GPS user.

The Precise Code, or P-Code has an effective wavelength of about 30 meters and is primarily for military applications. For this reason it is usually encrypted with the Y-Code and is generally not directly available to the civilian user. This encryption process is known as anti-spoofing (A-S). P-Code is referred to as the Precise Positioning Service or PPS.

Each satellite is equipped with several extremely precise atomic clocks used to generate timing information. Each satellite also generates a navigation message on both carrier frequencies which contains ephemeris, clock corrections and coefficients, the health and status of the satellites, the almanacs of all the satellites and other general information.

5.5 GPS Observables

There are two types of GPS observables of interest to the MDOT surveyor. The first is the pseudo range or the distance from the satellite to the receiver, the second is the carrier phase or the difference between the phase of the carrier signal transmitted by the satellite and the phase of the receiver oscillator at the epoch of measurement.[4] Pseudo ranging is used in many GPS receivers to determine initial coordinate values while carrier phasing is used for high precision. Pseudo ranging makes use of the codes, carrier phasing the signal carrying the codes.

5.5.1 Pseudo Range

The foundation of pseudo ranging is comparing the code(s) generated by the satellite with replicas of the same code(s) being generated by the receiver.

The pseudo range observable is defined as:[5]

$$\mathbf{P^i_A = \rho^i_A + c(\delta t^i - \delta t_A) + \delta^i_{A\,iono} + \delta^i_{A\,trop} + \varepsilon}$$

where:

$P^i_A = c(t_A - t^i)$ = measured pseudo range from satellite *i* to receiver *A* (meters)

t_A = time of reception of signal (seconds)

t^i = time of transmitting signal (seconds)

c = vacuum speed of light (meters/second)

ρ^i_A = geometric range (meters)

$= [(U^i - U_A) + (V^i - V_A) + (W^i - W_A)]^{½}$ in which $(U,V,W)^i$ and $(U,V,W)_A$ are the topocentric coordinates of a given satellite and of the point of interest respectively.

δt^i = satellite clock error (seconds)

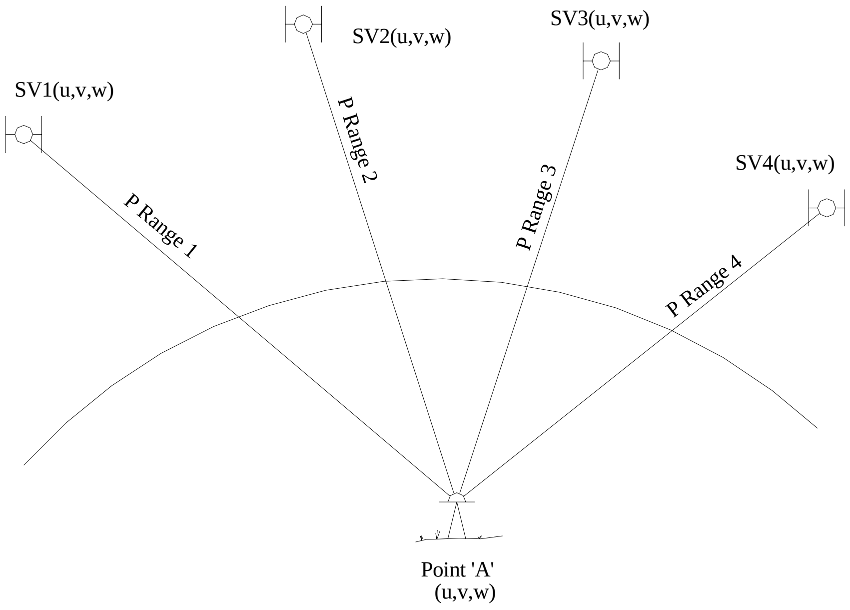
δt_A = receiver clock error (seconds)

$\delta^i_{A\ iono}$ = ionospheric error (meters)

$\delta^i_{A\ trop}$ = tropospheric error (meters)

ε = multi-path and receiver noise (meters)

Figure 5-2
Pseudo Ranging



To solve for the unknowns $(U,V,W)_A$ and for $c\delta t_A$ (time differentials), a minimum of four satellites is needed.

The user is encouraged to consult the endnotes at the back of this chapter or the bibliography at the end of **Chapter VII** for detailed explanations and derivations of terms and values that may not be familiar.

5.5.2 Carrier Phase

The foundation of carrier phasing is comparing the carrier signal(s) generated by the satellite with a replica of the carrier signal(s) generated within the receiver. Similarities exist between carrier phasing and measuring a distance with an EDM. "... The difference in the phase of an incoming signal with the phase of the internal reference reveals the fractional part of the carrier phase measurement in GPS." [6]

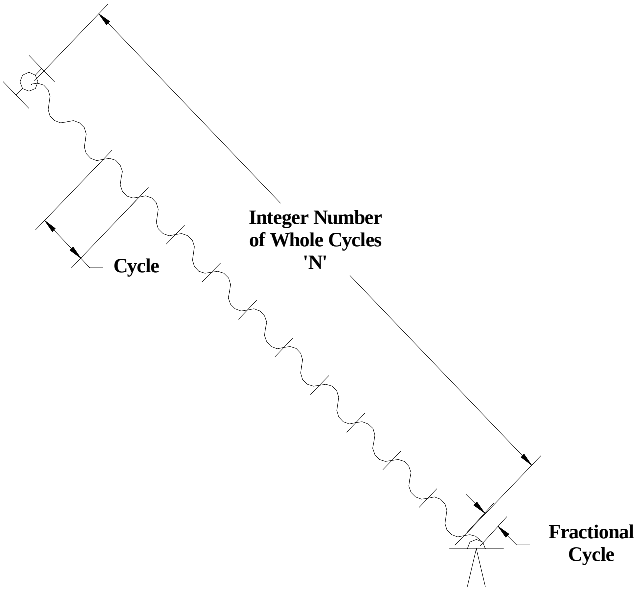
Carrier phasing is used in a relative observational mode, meaning that multiple receivers, occupy multiple points and simultaneously observe the same multiple satellites. The observational model for carrier phasing is defined as:[7]

$$\Phi^{i}_{A} = f\delta^{i} - (1/\lambda)(\rho^{i}_{A}) - f\delta_{A} + N^{i}_{A} - f\,\delta^{i}_{A\ \mathrm{iono}} + f\,\delta^{i}_{A\ \mathrm{trop}} + \varepsilon$$

where:

Φ^{i}_{A} = carrier phase measurement, in cycles for satellite *i* and receiver A
c = vacuum speed of light (meters/second)
ρ^{i}_{A} = geometric range (meters)

Figure 5-3
Carrier Phasing



λ = carrier wavelength (meters) (L1 or L2)

δ^i = satellite clock error (seconds)

δ_A = receiver clock error (seconds)

N^i_A = integer ambiguity (cycles)

$\delta^i_{A\ iono}$ = ionospheric error (meters)

$\delta^i_{A\ trop}$ = tropospheric error (meters)

ε = multipath and receiver noise (meters)

The chief difficulty in solving the carrier phase algorithm is determining the whole number of cycles (N^i_A) i.e., the integer ambiguity. A number of methods have been developed to do this. Generally with those observation methods employing long observation times techniques such as long term averaging are used. Integer ambiguity can also be resolved by using carrier phasing in combination with pseudo ranging and carrier beat measurements, techniques adapted in the higher productive observation methods.

Carrier phasing provides a more accurate solution than pseudo ranging due to the shorter wave lengths of the L1 (19 cm) and L2 (24 cm) carrier signal as opposed to the longer C/A-Code (300 meter) or P-Code (30 meter) and the ability to resolve the carrier phase down to about 2 mm (EM,6-1).

Again the user is encouraged to consult the bibliography at the end of this Part for further explanation and guidance.

5.6 GPS Receivers

EM 1110-1-1003 “NAVSTAR Global Positioning System Surveying” provides criteria for choosing the appropriate GPS survey package. These criteria are: the applications for which the receiver will be used, accuracy requirements, power requirements, operational environment, processing environments, costs.[8]

5.6.1 Applications

Before spending tens of thousands of dollars on a GPS survey package the prudent surveyor will go through a thorough cost to benefit analysis. GPS is only profitable if it is used, used often, and used appropriately. Many survey grade GPS packages will support an MDOT project. No GPS package will profitably support all MDOT projects. Design Survey applications include primary and intermediate control, photo control, boundary surveys, topographic surveys and many others. Each of these has unique requirements that may or may not lend themselves to any given GPS package. The surveyor should look at specific applications and specific observational modes to support those applications before making a final decision.

5.6.2 Accuracy Requirements

Any GPS receiver used on an MDOT project must be of survey grade and be capable of carrier phasing in a relative mode. Single and dual frequency receivers both have advantages and disadvantages. Single frequency receivers cost less. Dual frequency receivers will typically provide the MDOT surveyor with more options depending upon hardware and software add ons. Dual frequency receivers will also enable the MDOT surveyor to observe longer base lines with greater precision. Many, but not all, MDOT applications require dual frequency receivers.

5.6.3 Power Requirements

Powering a high grade GPS receiver over long, continuous periods may provide quite a logistical challenge. Extra batteries are always needed. Options to use standard 12 volt vehicle batteries should be considered. Batteries can be heavy and bulky, a serious consideration when conducting a GPS campaign in remote areas.

5.6.4 Operational Environment

GPS receivers are generally very sturdy, well built precision instruments. Accessories may or may not be. Where the receiver is to be used and in what type of weather conditions should be factored into the decision making process. Peripherals such as carrying cases, power and antenna cables, plugs and jacks may seem only incidental but can make or break a campaign.

5.6.5 Processing Environments

Post processing is a fact of life for many MDOT GPS applications. Software must meet or exceed requirements, be relatively easy to use and most importantly be understood by the user. GPS software is solving millions of very complex and integrated algorithms. The GPS surveyor must know and understand the theory behind the system and be able to accurately interpret and evaluate the results.

5.6.6 Cost

Like any asset, GPS is a tool whose value lies in the profits it can generate. Besides purchase costs, the surveyor needs to look at training costs. The GPS learning curve can be long and rough if the people who are going to use it lack the proper formal education in mathematics, statistics, physics and geodesy or if they are not given sufficient time to learn field and office techniques. The cost of rigorous and realistic training should be factored into any GPS purchase. Those who take short cuts with training in the short term will pay dearly in the long run.

5.7 GPS Observation Techniques

Table 5-1
Carrier Phase Tracking Techniques

Method	Minimum Requirements	Applications	Accuracy
Classic Static (Post Processing)	• L1 or L1/L2 Receiver • 45 min to 1 hr minimum processing time	• Primary Control (L1/L2) • Secondary Control (L1 or L1/L2)	Sub-centimeter
Rapid Static (Post Processing)	• L1/L2 Receiver • 5 to 20 min observing time (1)	• Secondary Control • Photo Control	Sub-centimeter
Kinematic (2) (Post Processing)	• L1 Receiver with kinematic survey option	• Continuous Topo • Location Surveys	Centimeter
Stop and Go (Post Processing)	• L1 Receiver	• Secondary Control • Photo Control	Centimeter
Pseudo-Kinematic (3) (Post Processing)	• L1 Receiver • 2 5-10 minute periods separated by 1 hour	• Secondary Control • Photo Control	Centimeter
Real Time Kinematic (4) (Real Time or Post Processing)	For post processing • L1/L2 Receiver For real time • L1/L2 Receiver • Internal or External Processor • Min 4800 baud radio/modem data link	• Location Surveys • Continuous Topo	Sub-decimeter

(1) Dependant upon satellite constellation and number of satellites in view

(2) Initialization period required and loss of satellite lock not tolerated
(3) Satellite lock must be maintained during sessions. Same 4 satellites must be in view for both sessions. Satellite lock need not be maintained between sessions. Antenna heights must be the same between sessions.
(4) No initialization period required. Integer ambiguity resolved while moving. Loss of satellite lock is tolerated.

(Adapted from Table 6-1, EM 1110-1-1003, 1Aug 96)

Table 5-1 provides in tabular form GPS carrier phase observation methods, minimum requirements, applications and expected accuracies at the 95% confidence level. Further guidance on these various techniques can be found below.

Classic Static

- Extended continuous observation period (greater than 45 minutes)
- Simultaneous observations made with two or more receivers with a common data rate to four or more satellites
- Carrier phase observations made on one or both frequencies
- Triple difference baseline measurements used to identify cycle slips and clean data
- Double differencing to resolve integer terms
- Various mathematical models account for satellite orbits, atmospheric refraction. Carrier phase ambiguities can be fixed or allowed to float

Pseudo-Kinematic

- Simultaneous observations made from base station with one or more rovers
- Two or more observations of relatively short duration (5 to 10 minutes) of the same baseline taken at least one hour apart to allow significant change in satellite geometry
- Carrier phase observations on one or both frequencies
- Same satellites, four or more, observed in each session with a constant antenna height
- Change in satellite geometry exploited to resolve integer terms with double difference processing
- Continuous lock between sessions is not required.

Rapid Static

- Simultaneous observations made from base station with one or more rovers
- Single baseline occupation of two to ten minutes observing 5 or 6 satellites
- Multiple observables (C/A, P, Y code; L_1, L_2, carrier phase)
- Least squares ambiguity resolution in a limited search space

- Reliability enhanced with multiple occupations

Stop and Go

- Simultaneous observations by base station and one or more rovers to four or more satellites
- Lock must be maintained during entire session
- Survey begun by observing a previously determined baseline or by performing antenna swap (initialization)
- Prior knowledge of carrier phase ambiguities allows for double difference solution with a minimum of data
- Suitable for wide open terrain only

Kinematic (Continuous Kinematic)

- Like Stop and Go but there is no stopping
- Vectors created which are associated with single epochs

Real Time Kinematic (RTK)

- Simultaneous observations by base station and one or more rovers to at least five satellites
- Radio link established between base and rovers
- Focus on resolution of errors in single position (rover) rather than relative position between stations
- Best suited for general topographic data collection and layout applications

The surveyor must thoroughly understand the purpose and accuracy requirements of the project before selecting the methodology. Any use of GPS should be coordinated with the Survey Project Manager. Expected accuracies are in horizontal components. For vertical components refer to section 5.12.

5.8 Mission Planning

Planning a successful GPS campaign includes equipment selection, point selection, determination of satellite availability, site reconnaissance and selection of the survey scheme.[9]

Equipment selection is a function of the size of the project, the purpose of the project and the standards of precision to be met.

Point selection is determined by the scope of work and the availability of reliable horizontal and vertical control.

Satellite availability may be estimated from software available with virtually all survey grade GPS systems.

Site reconnaissance includes finding existing points, determining the optimum location for and the setting of monuments, also completing reconnaissance reports and station visibility diagrams when required.

Selecting the survey scheme includes choosing the appropriate GPS observational technique along with observation schedules

5.9 Classification, Standards of Accuracy and General Specifications for GPS Surveys

See Part VII, Control Surveys.

5.10 Sources of Error

The Global Positioning System is affected by a number of systematic errors. The major ones are listed here along with brief descriptions.

5.10.1 Signal Degradation (Selective Availability and Anti-spoofing)

For national security purposes timing and satellite positional information may be deliberately degraded by the Department of Defense through a process of Selective Availability (SA). Selective availability primarily effects point positioning using the C/A code where a single receiver occupies a single point. Using GPS in a relative mode where multiple receivers are used and points whose positions are known are tied into a network probably eliminates most of the effects of Selective Availability. Precise ephemeris data is available from the National Geodetic Survey (NGS). See Part VII, Control Surveying.

The Department of Defense has the ability to basically "turn off" the P-Code or to invoke an encrypted Y-Code as a measure of denying access to the P-Code. The purpose is again security to keep adversaries from sending false signals with the GPS signature to create confusion. When Anti-Spoofing is activated a special decoding device available only to certain authorized users is required to directly access the P-Code.[10]

5.10.2 Timing Errors

Solving any of the ranging algorithms reduces to determining the time of signal travel. Since multiple clocks in multiple satellites and different clocks in different receivers are being simultaneous used, solving all clock errors is critical. Numerous methods of accomplishing this have been developed and some will be discussed in this chapter under post-processing.

5.10.3 Multi-Path

Under ideal conditions, a signal would travel directly from a satellite to a receiver. Objects close to the receiver may cause the signal to “bounce” into the antenna and affect the range solution. Using a ground plane on the antenna and avoiding positioning the receiver near objects such as buildings, trees or utility poles will aid in the elimination of multi-path effects.

5.10.4 Atmosphere

A GPS signal traveling through the atmosphere can be delayed or accelerated by ionospheric and tropospheric effects. Precisely modeling these effects can prove very challenging. Atmospheric effect can be minimized by keeping base lines relatively short so that atmospheric effects are relatively constant among multiple receivers or by using dual frequency receivers and employing L1/L2 differencing techniques.

5.10.5 Antenna Phase Center Variations

The physical center of the GPS receiver antenna may not coincide with the electronic center. By using antennas of the same type and by orienting all receiver antennas to the same direction, typically North, this source of error can be minimized.

5.10.6 Height of Instrument

GPS is an integrated, three dimensional system. Unlike lower order classical surveys where horizontal position is determined by observing angles and distances and elevations are determined by differential leveling in separate and independent operations, such is not the case with GPS. Errors in determining the height of the antenna will propagate not only into vertical positions but into horizontal as well. Height from the ground to the antenna center must be measured accurately. For precise surveys the deflection of the vertical must be taken into account.

5.10.7 Satellite Geometry

Arguably the most critical factor in a successful GPS campaign is the number and the location of available satellites. At least four satellites must be visible for a three dimensional solution. Ideally the four satellites will be well disbursed, one in each quadrant, and at different elevation angles from the receiver’s position. Additional satellites are required for some of the newer highly productive observation techniques. MDOT projects are often located in long, narrow corridors in highly developed or in highly forested areas. What may be ideal conditions under a sterile office scenario, turns into a night mare in the field. The following are some suggestions for the MDOT route surveyor employing GPS in such a situation.

- Have well defined control points in clear areas completely surrounding the project area.
- Never observe outside of the perimeter defined by the control points.
- Prepare obstruction diagrams on all control points as well as on a sampling of points in the corridor. Factor obstructions into the satellite visibility diagrams to estimate the best observation times.

- Observe elevations on a random sampling of points in the corridor using differential leveling, both near the centerline and out on the "wings". Combine with the best geoid model available to estimate ellipsoid heights. This will provide "check points" on the final solution and provide additional information to the processor and may "save a satellite". With an established ellipsoid height, the solution reduces to two dimensions.
- Use multiple observations on points from different control points with different satellite geometry.

5.10.8 Dilution of Precision

Dilution of Precision (DOP) is a measure of the quality of the satellite geometry. The lower the DOP, the more favorable the conditions. Conversely, the higher the DOP, the more precision is being diluted and the worse the conditions. DOP factors near 4 are considered ideal. If the DOP is above 10, GPS should not be used. DOP is the square root of the trace of the cofactor matrix (Qxx) of the observation equations solving for the adjusted coordinates and clock error (ϕ, λ, h, δt) of the point of interest.[11]

$$DOP = [Tr(Qxx)]^{1/2} = [Tr(1/\sigma_0^2 \Sigma xx)]^{1/2}$$

σ_0^2 = estimated reference variance

Σxx = covariance matrix for (ϕ, λ, h, δt)

DOP may be reported as a function of different combinations of variables.

GDOP or Geometric Dilution of Precision = $\dfrac{\sqrt{\sigma_\varphi^2+\sigma_\lambda^2+\sigma_h^2+c^2\sigma_{\delta t}^2}}{\sigma_0}$

PDOP or Position Dilution of Precision = $\dfrac{\sqrt{\sigma_\varphi^2+\sigma_\lambda^2+\sigma_h^2}}{\sigma_0}$

HDOP or Horizontal Dilution of Precision = $\dfrac{\sqrt{\sigma_\varphi^2+\sigma_\lambda^2}}{\sigma_0}$

VDOP or Vertical Dilution of Precision = $\dfrac{\sigma_h}{\sigma_0}$

TDOP or Time Dilution of Precision = $\dfrac{\sigma_{\delta t}}{\sigma_0}$

where (σ_ϕ, σ_λ, σ_h) = standard deviations in latitude, longitude and height.

$\sigma_{\delta t}$ = standard deviation of the clock offset

c = speed of light in a vacuum

5.11 Post Processing GPS Data

Post processing involves solving a series of interconnected algorithms and results in elimination of many of the errors or biases inherent in the Global Positioning System. Post processing results in baseline solutions (dx,dy,dz) between points and includes network adjustments. Biases are accounted for and baselines are determined in the first phase then the network is adjusted in the second phase.

5.11.1 Differencing

At the heart of post processing are a series of differencing algorithms.

5.11.1.1 Single Differencing

A single difference is the difference in the simultaneous carrier phase measurements from one GPS satellite as measured by two receivers.[12] A single difference can also be the difference in the simultaneous phase measurements from two satellites as measured by a single receiver. With two receivers simultaneously observing a single satellite, satellite clock error is eliminated. With a single receiver observing two satellites, receiver clock error is canceled. This is due to the fact that in both cases, a single clock is used.

5.11.1.2 Double Differencing

Double differencing combines the two modes of single differencing. Two receivers are simultaneously observing the signals from two satellites. Double differencing eliminates the clock biases from both sources and since the atmospheric effects on the satellite signals over relatively short baselines are for practical purposes identical, eliminates most of the atmospheric effects. Using dual frequency receivers adds additional information to the solution improving the resolution of atmospheric biases and thus allows for the resolution of longer baseline vectors.

5.11.1.3 Triple Differencing

The triple difference is the difference between two double differences. In the triple difference solution, the numbers of integer cycles (N) from satellites to receivers cancel. The triple difference solution, then, can aid in fixing cycle slips or temporary losses of lock.

When a receiver locks on to a satellite signal, the lock will occur at some fraction of a cycle. This fraction will remain a constant as long as lock is maintained. The triple difference solution can resolve this fractional cycle.

When a receiver locks on to a satellite signal, there are a whole number of cycles in addition to the fractional cycle just described. While this initial number of whole cycles is not known, it is a constant number as long as lock is maintained. While the number of integer cycles between the satellite and receiver will change with each epoch due to the movement of the satellites, that initial value remains the same. It then provides a reference value which when added to the fractional cycle previously described and the difference in cycle counts between one epoch and another provides an estimate of total cycle count between satellite and receiver.

5.11.2 Baseline Resolution

The data flow in post processing typically follows this path.[13]

a. An initial approximation of the receiver position is computed from pseudo range data.

b. Triple differencing provides initial baseline (dx,dy,dz) estimates.

c. Double difference equations are formed and solved yielding a fractional number of integer cycles, refined base line estimates, covariance data and confidence estimates. Key here is fractional number of integer cycles. This is an estimate of N which by definition is a whole number. This value is referred to as the "float" double difference solution.

d. If the float double difference solution is acceptable, N is rounded off to the nearest whole integer resulting in the "fixed" double difference solution. Final base line components (dx, dy, dz) are determined with covariance data, reliability and confidence estimates.

All steps resulted in an answer. The best answer and the one with the greatest reliability is the fixed double difference solution.

5.11.3 Network Adjustment

When base line components have been computed, they are entered into a three dimensional, nearly linear, least squares network adjustment. In classical surveying, angles are observed, distances are measured and elevations are determined. The surveyor may have a great deal of confidence in the individual parts, but (s)he will always use these data to form a geometrically closed figure to see how all the data fits together. We are at this point with GPS post processing. We have the individual parts, the dx, dy, dz base line components, but we do not know how well they fit together.

There are actually two adjustments that are made. The first is a minimally constrained or "free net" adjustment, the second a fully constrained adjustment. The first is made without factoring in known control point values (ϕ, λ, h). This free net adjustment sets an arbitrary point as an anchor and provides a quality check on the interrelationship of the base line vectors. This is a "somewhere in space" solution that is not the final solution.

The fully constrained solution factors in known control point values and “fixes” the network on the ground. It should be performed only after an acceptable free net adjustment. The fully constrained adjustment provides the surveyor with an estimate of the quality of published control points as well as insurance that any receiver really occupied the point that the surveyor thought that it did.

If the free net adjustment fails, the surveyor needs to find and eliminate the source of the problem before proceeding to the fully constrained adjustment. Baseline post processing will typically yield more base line solutions that the surveyor needs.

5.11.4 Local Accuracy versus Network Accuracy

FGDC standards define local and network accuracies. The definitions are repeated here for convenience.

network accuracy - The *network accuracy* of a control point is a value that represents the uncertainty in the coordinates of the control point with respect to the geodetic datum at the 95-percent confidence level. For NSRS network accuracy classification, the datum is considered to be best expressed by the geodetic values at the Continuously Operating Reference Stations (CORS) supported by NGS. By this definition, the local and network accuracy values at CORS sites are considered to be infinitesimal, i.e., to approach zero.[14]

local accuracy - The *local accuracy* of a control point is a value that represents the uncertainty in the coordinates of the control point relative to the coordinates of other directly connected, adjacent control points at the 95-percent confidence level. The reported local accuracy is an approximate average of the individual local accuracy values between this control point and other observed control points used to establish the coordinates of the control point.[15]

Local accuracy provides practical information for users conducting local surveys between control monuments of known position. NGS will be publishing local accuracy numbers along measured lines. To determine the local accuracy (dL_{ij}) of a line between two existing monuments that have not been directly connected, the following formula may be used.[16]

$$dL_{ij} = [(dN_i)^2 + (dN_j)^2]^{1/2}$$

where: dN_i = network accuracy for point i
dN_j = network accuracy for point j

5.12 Vertical Surveying with GPS

For a number of reasons, the height component of a three dimensional position determined with GPS is its weakest element. Standard deviations of heights can differ from standard deviations of horizontal components by a factor of 10. Among the reasons for this are the geometry of the satellites (A fifth satellite located at the center of the earth would solve this problem!), lack of sufficient, reliable vertical control points, limitations in geoid models, the deflection of the vertical and others beyond the scope of this manual. While much successful research is being conducted in this area it is not recommended at this time that the surveyor rely on the Global Positioning System alone for determining higher order elevations.

For lower order MDOT surveys, considerable success has been achieved by factoring in observed orthometric heights in the GPS network adjustment. Certain elevations are held fixed, others are constrained to a relatively low standard deviation, still others are allowed to float and serve as check points. The relative accuracy of the GEOID model being used is critical. Some network adjustment programs will allow the user to fix both the ellipsoid height **and** the orthometric height of a point, thus deriving his or her own geoid height. Others will allow for fixing the ellipsoid height **or** the orthometric height and force the user to use the programmed geoid model.

End Notes

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14. Federal Geodetic Control Subcommittee, Federal Geographic Data Committee, *Geospatial Positioning Accuracy Standards* (Reston, VA: U.S. Geologic Survey, 1998)

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