# CHAPTER 5

## Differential or Relative Positioning Determination Concepts

5-1. General. Absolute/autonomous point positioning, as discussed earlier, will not provide the accuracies needed for most USACE mapping and control projects due to existing and induced errors in the measurement process. In order to minimize these errors and obtain higher accuracies, GPS can be used in a relative or differential positioning mode--i.e. Differential GPS. Throughout this manual, the terms "relative" and "differential" positioning have similar meaning. This chapter covers the basic theory and concepts of differential GPS positioning as it applies to engineering and construction surveys.

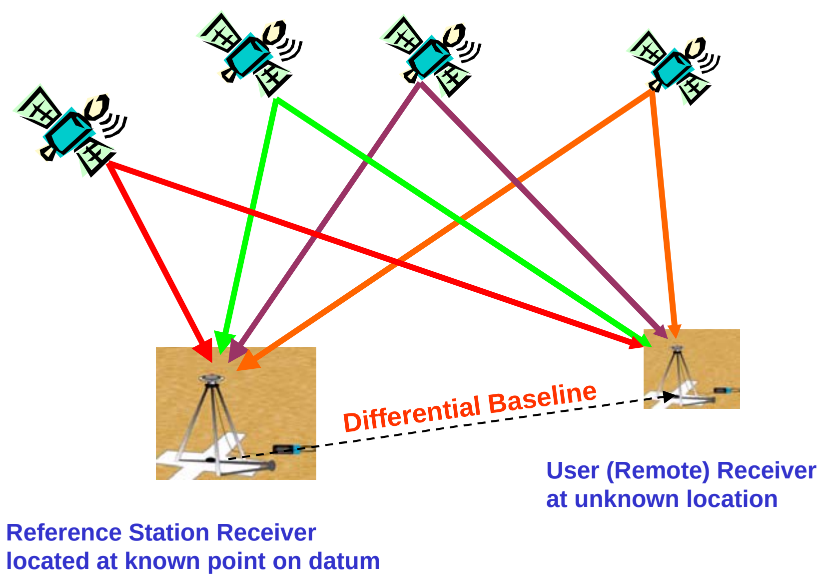


Figure 5-1. Differential or Relative GPS positioning

5-2. Differential Positioning Concepts. As stated in Chapter 2, differential GPS positioning is simply a process of determining the relative differences in coordinates between two receiver points, each of which is simultaneously observing/measuring satellite code ranges and/or carrier phases from the GPS satellite constellation. These differential observations, in effect, derive a differential baseline vector between the two points, as illustrated in Figure 5-1. This method will position two stations relative to each other--hence the term "relative positioning"--and can provide the higher accuracies required for project control surveys, topographic surveys, and hydrographic surveys. There are basically two general types of differential positioning:

Code phase pseudorange tracking
Carrier phase tracking

Both methods, either directly or indirectly, determine the distance, or range, between a GPS satellite and a ground-based receiver antenna. These measurements are made simultaneously at two different receiver stations. Either the satellite's carrier frequency phase, or the phase of a digital code modulated on the carrier phase, may be tracked--depending on the type of receiver. Through various processing techniques explained below, the distances between the satellites and receivers can be resolved, and the relative positions of the two receiver points are derived. From these relative observations, a baseline vector between the points is generated. The resultant positional accuracy is dependent on the tracking method used--carrier phase tracking being far more accurate than code phase tracking.

5-3. Differential Positioning (Code Pseudorange Tracking). Code pseudorange tracking is the most widely used differential GPS positioning technique. It can deliver "meter-level" positional accuracies that typically range between 0.5 m to 5 m, depending on the code DGPS reference network and user receiver type. It is the technique used for maritime navigation, including USACE hydrographic surveying and dredge location applications. It is also used for air and land navigation where meter-level accuracy is required. Differential positioning using code pseudoranges is performed similarly to the absolute/autonomous positioning techniques described in Chapter 4; however, some of the major clock error and atmospheric uncertainties are effectively minimized when simultaneous observations are made at two receiver stations. Errors in satellite range measurements are directly reflected in resultant coordinate errors. Differential positioning is not so concerned with the absolute position of the user but with the relative difference between two user positions who are simultaneously observing the same satellites. Since errors in the satellite position ($X^s$, $Y^s$, and $Z^s$) and atmospheric delay estimates ( $d$ ) are effectively the same (i.e. highly correlated) at both receiving stations, they cancel each other to a large extent. Equation 4-1, which represents a general pseudorange observation, is repeated as Equation 5-1 below.

$$R = p^t + c(\Delta t) + d \qquad \text{(Eq 5-1)}$$

where

$R$ = observed pseudorange
$p^t$ = true range to satellite (unknown)
$c$ = velocity of propagation
$\Delta t$ = clock biases (receiver and satellite)
$d$ = propagation delays due to atmospheric conditions

The clock biases ( $\Delta t$ ) and propagation delays ( $d$ ) in the above equation are significantly minimized when code phase observations are made with two receivers. This allows for a relatively accurate pseudorange correction ( $R - p^t$ ) to be computed at the receiver station set over a known point. This is because the true range ( $p^t$ ) to the satellite can be determined from inversing between the ground station's coordinates and the broadcast satellite coordinates. If the pseudorange correction ( $R - p^t$ ) is computed for 4 or more satellites, these pseudorange corrections can be transmitted to any number of user receivers to correct the raw pseudoranges originally observed. If 5 or more pseudorange corrections are observed, then a more reliable and redundant position computation is obtained. If more than one "reference station" is used to obtain pseudorange corrections, then the corrections may be further refined using the network of reference stations. Networks of stations transmitting differential GPS code correctors are termed as "augmented" GPS, or a wide area augmented system. Pseudorange corrections are broadcast by standard RF, satellite link, cell phone, or other transmission media. Satellite communications links are typically used for wide area augmentation networks. An alternate differential correction technique computes the position coordinate differences at the reference station and broadcasts these coordinate differences as correctors. This method is not widely used.

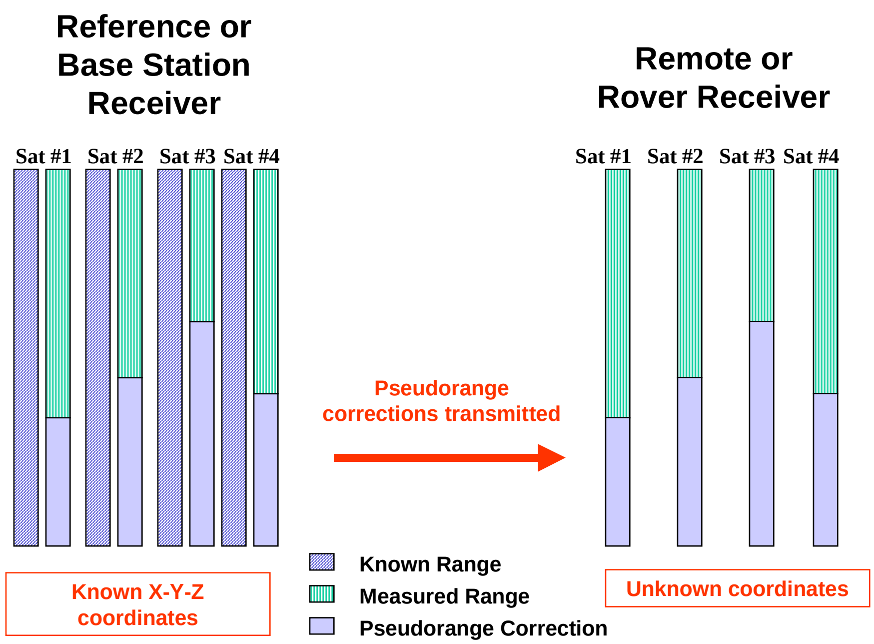


Figure 5-2. Determining pseudorange correction at a differential GPS reference station. Corrections are computed for satellites in view and broadcast to remote receivers.

a. For a simplified example, if the true range from a "known" GPS reference control point to a satellite is 20,000,000m and the observed or measured pseudorange distance was 19,999,992 m, then the pseudorange error or correction is + 8 m (20,000,000-19,999,992) for that particular satellite. A similar pseudorange correction (or PRC) can be generated for each satellite being observed from the known GPS reference station, as illustrated in Figure 5-2. If a second "rover" receiver is observing at least four of the same satellites as the reference receiver, and is within a reasonable distance (say 300 kilometers) from the reference receiver, it can use these same PRCs to correct the rover receiver's observed pseudoranges since the range errors will be similar at both points. If the rover receiver is located equidistant between two reference stations (i.e. a wide area GPS network), and the second reference station observed a PRC of + 10 m on the same satellite, then an adjusted PRC of 9 m ((8+10)/2) could be used at the rover receiver. Additional wide area reference stations provide better modeling of the PRCs at the rover receiver, although the density and distance from reference stations is still critical for accuracy improvements.

b. This differential code pseudoranging process results in coordinates of the user on the earth's surface that are relative to the datum of the reference station. Therefore, when you are using GPS in a relative mode, you are referenced to the GRS80 ellipsoid in most cases due to the fact that your base station (i.e. CORS, Coast Guard Beacons, etc…) are referenced to NAD83 not WGS84. For example, if the reference station is computing PRCs using NAD83 (1996) coordinates, then the resolved coordinates at the rover receiver will be in this same system. These NAD83 (1996) coordinates can be transformed to another datum and coordinate system (e.g., NAD27 SPCS) using known local transformation differences, such as those obtained from CORPSCON. This can be done in real-time. Therefore, GPS coordinate differences can be applied to any type of local project reference datum (i.e. NAD 27, NAD83, or any local project grid reference system).

c. Code pseudorange tracking has primary application to real-time navigation systems where accuracies at the 0.5 to 5 m level are tolerable. Given these tolerances, USACE engineering survey applications for code pseudorange tracking GPS are hydrographic surveying, dredge positioning, and some GIS feature mapping work. Newer hand-held receivers capable of acquiring government or commercial wide area network PRCs will provide accuracies at the 1 to 3 m level, and can be used for populating GIS databases. Descriptions of real-time code phase tracking systems used for hydrographic surveying and dredge positioning are contained in EM 1110-2-1003.

5-4. Differential Positioning (Carrier Phase Tracking). Differential positioning using carrier phase tracking uses a formulation of pseudoranges similar to that done in code or absolute/autonomous GPS positioning. However, the process becomes somewhat more complex when the carrier signals are tracked such that range changes are measured by phase resolution. The modulated codes are removed from the carrier, and a phase tracking process is used to measure the differences in phase of the received satellite signals between the reference receiver and the user's receiver at an unknown point. The transmitted satellite signal is shifted in frequency due to the Doppler effect. The phase is not changed. GPS receivers measure what is termed the carrier phase "observable"--usually symbolized by " $\phi$ ". This observable represents the frequency difference between the satellite carrier and that generated in the receiver, or a so-called "beat" phase difference. This phase measurement observation can be shown in the following expression for the carrier phase observable (Kaplan 1996):

$$\phi_k^P(t) = \phi_k^P(t) - \phi^P(t) + N_k^P + S_k + f\tau_P + f\tau_k - \beta_{iono} + \delta_{tropo} \qquad \text{(Eq 5-2)}$$

where

$\phi_k^P(t)$ = length of propagation path between satellite "P" and receiver "k" ... in cycles
$\phi_k^P(t)$ = received phase of satellite "P" at receiver "k" at time "t"
$\phi^P(t)$ = transmitted phase of satellite "P"
$N_k^P$ = integer ambiguity
$S_k$ = measurement noise (multipath, GPS receiver, etc.)
$f$= carrier frequency (Hz)
$\tau_P$ = satellite clock bias
$\tau_k$ = receiver clock bias
$\beta_{iono}$ = ionospheric advance (cycles)
$\delta_{tropo}$ = tropospheric delay (cycles)

For more details on these carrier phase observation models, see also Remondi (1985), Leick (1995), Van Sickle (2001), and other texts listed at Appendix A.

a. Typically, two receivers will be involved in carrier phase observations, and 4 or more satellites will be measured from both receivers. One of the receivers will be placed at a known reference point--the "reference" receiver. The other receiver is usually referred to as the "remote" or "rover" receiver--and is located a point where a map feature or project control point coordinate is required. This "rover" receiver may be stationary over the unknown point--i.e. "static"--or it may be roving from unknown point to unknown point--i.e. "kinematic."

b. Interferomic "differencing" techniques are used to resolve carrier phase observations made at the two receivers. Differencing involves forming linear combinations between phase observations. To eliminate clock errors in the satellite, a "single difference" between phase measurements of the reference and remote receivers is performed. Single differencing between receivers eliminates the satellite clock error. This single differencing "between receivers" procedure is performed for all the mutually observed satellites, and the resultant single differences are subsequently differenced "between satellites" (i.e. "double differenced"), thus eliminating the receiver clock error. Double-differenced measurements on three pairs of satellites will yield the difference between the reference and remote locations. "Triple differencing" is the difference of two double differences performed over two different epochs. Triple differencing "between epochs" is used to indirectly resolve the number of whole carrier cycles between the satellite and receiver. There are a number of methods used to determine the integer ambiguity (the number of unknown integer cycles). These range from physical placement of the remote receiver a known distance from the reference receiver to automated Kalman filtering and searching methods. These differencing techniques are more fully described in Chapter 10.

5-5. <u>Carrier Phase Survey Techniques</u>. Carrier phase tracking provides an accurate satellite-receiver range resolution due to the short carrier wavelengths (approximately 19 cm for L1 and 24 cm for L2) and the ability of a receiver to resolve the carrier phase down to about 2 mm. This technique, therefore, has primary application to engineering, construction, topographic, and geodetic surveying, and may be employed using either static or kinematic methods. There are several techniques that use the carrier phase in order to determine the position of a remote receiver. These generally break down to static and kinematic methods; however, both methods have similar observation and initialization requirements, and differ mainly in their initialization procedures and whether the positional computations are performed in real-time or post-processed. In practice, some "kinematic" methods actually observe baselines in a "static" mode. Different receiver manufacturers have varying terminologies and techniques for these methods. The basic concepts of some of the most common survey techniques are explained below, and field procedures for some of these methods can be found in Chapter 9. Table 5-1 summarizes these techniques, their associated accuracies, applications, and required components.

Figure 5-3. (Left) GPS surveys at Corps Huntsville, AL Training Center--Survey IV PROSPECT Course (2002) and (right) New Orleans District GPS control surveys along Mississippi River at District Office base

a. Static. Static surveying (Figure 5-3) is the most widely used differential technique for precise control and geodetic surveying. It involves long observation times (30 minutes to 6+ hours, depending on the number of visible satellites, baseline length, accuracy requirements, etc.) in order to resolve the integer ambiguities between the satellite and the receiver. Accuracies in the sub-centimeter range can be obtained using the static surveying methods. Either single-frequency or dual-frequency receivers may be used.

b. Rapid Static. The concept of Rapid Static is similar to Pseudo Kinematic described below. It is used to measure baselines and determine positions at the centimeter-level with short, static observation times--e.g., 5-20 minutes. The observation time is dependent on the length of the baseline and number of visible satellites. Loss of lock, when moving from one station to the next, can also occur since each baseline is processed independent of each other. Unlike Pseudo Kinematic, stations are occupied only once. Dual-frequency receivers are required.

c. Kinematic. Kinematic surveying is a GPS carrier phase surveying technique that allows the user to rapidly and accurately measure baselines while moving from one point to the next, stopping only briefly at the unknown points, or in dynamic motion such as a survey boat or aircraft. A reference receiver is set up at a known station and a remote, or rover, receiver traverses between the unknown points to be positioned. The data is collected and processed (either in real-time or post-time) to obtain accurate positions to the centimeter level. Kinematic survey techniques require some form of initialization to resolve the carrier phase ambiguities. This can be done by setting the remote receiver on a known baseline relative to the reference receiver, by performing an "antenna swap" procedure between the two receivers, and other techniques such as "On-the-Fly" or OTF.

d. Stop & Go Kinematic. Stop and Go Kinematic involves collecting static data for several minutes (i.e. 10-30 minutes) at each station after a period of initialization to gain the integers. This technique does not allow for loss of satellite lock during the survey. If loss of satellite lock does occur, a new period of initialization must take place. This method can be performed with two fixed or known stations in order to provide redundancy and improve accuracy.

e. Pseudo Kinematic. This technique is similar to Stop and Go Kinematic procedures. The main difference is that there is no static initialization. Unknown points must be double-occupied (approximately 5-10 minutes), and each unknown point must be revisited after about an hour. Unlike Stop and Go Kinematic, loss of satellite lock is acceptable.

f. Real-Time Kinematic (RTK). The RTK positioning methods will yield sub-decimeter accuracies in real-time. This method has become widely used for accurate engineering and construction surveys, including topographic site plan mapping, construction stake out, construction equipment location, and hydrographic surveying. This GPS technique determines the integer number of carrier wavelengths between the GPS antenna to the GPS satellite while the rover receiver is in motion and without static initialization. RTK typically uses an "On-the-Fly" (OTF) integer initialization process whereby initialization can be performed while the roving receiver is moving. Periodic loss of satellite lock can be tolerated and no static initialization is required to regain the integers. This differs from other GPS techniques that require static initialization while the user is stationary. A communication link between the reference and rover receivers is required. A number of techniques have been developed to increase RTK accuracies over local areas, such as placing simulated GPS satellite receivers at fixed ground locations (pseudolites). These have application in obscured areas (underground, tunnels, inside buildings, etc.) or for accurate aircraft landings.

g. Real-Time Network (RTN). One significant drawback of this single base RTK approach is that the maximum distance between reference and rover receiver must not exceed 10 to 20 kilometres in order to be able to rapidly and reliably resolve the carrier phase ambiguities. This limitation is caused by distance-dependent biases such as orbit error, and ionospheric and tropospheric signal refraction. These errors, however, can be accurately modelled using the measurements of an array of GPS reference stations surrounding the rover site. Thus, RTK positioning is extended from a single base to a multi-base technique. The success of RTK positioning in recent years resulted in the establishment of RTK positioning services which supply reference data to anybody who is willing to pay for them. In order to provide such a service to a larger region or a whole country many reference stations have to be set up and maintained. The development of Network RTK can result in a tremendous reduction of the investment costs necessary to start an RTK positioning service, since the number of reference stations can be reduced from about 30 reference stations per 10,000 square kilometers for single base RTK to 5 to 10 reference stations per 10,000 square kilometers for Network RTK. (Wanninger, Lambert, *Introduction to Network RTK.* With the convergence of maturing technologies such as wireless Internet communication, later generation GNSS hardware and firmware, and augmented satellite constellations, RTK positioning is becoming a preferred method of data acquisition, recovery and stake out to many users in diverse fields. NGS is moving toward “active” monumentation via the CORS network and its online positioning user service (OPUS). This is a departure from the traditional delivery of precise geodetic control from passive monumentation. Currently, network solutions for RTK positioning are sweeping across the United States. The cost to benefit ratio and ease of use are two main factors driving this rapid growth. RTN administrators span a wide sector of all GNSS users. Some examples of the RTN administrators that are part of this rapidly expanding GNSS application are State Departments of Transportation (DOT), Value Added GNSS Vendors, GNSS Manufacturers, Spatial Reference Centers, Geodetic Surveys, Academic Institutions, Scientific Groups, County Governments, City Governments, Private Survey/Engineering Companies and Agricultural Cooperatives. The Philadelphia District Corps of Engineers owns and operates a real-time network. Benefits to the user of an RTN over classical RTK positioning include:

(1) No user base station is necessary. Therefore, there are no security issues with the base, no control recovery is necessary to establish its position, and the user needs only half the equipment to produce RTK work. Additionally, there is no lost time setting up and breaking down the base station equipment and radio.

(2) The first order ppm error is eliminated (or drastically reduced) because ionospheric, tropospheric and orbital errors are interpolated to the site of the rover.

(3) The network can be positioned to be aligned with the NSRS with high accuracy. The users will then be collecting positional data that will fit together seamlessly. This is important to all users of geospatial data, such as GIS professionals who may deal with such regional issues as emergency management and security issues.

(4) Datum readjustments or changes can be done transparently to the user with no post campaign work. New datum adjustments to NAD83 or even transformations to another geodetic datum such as the International Terrestrial Reference Frame (ITRF) are done at the network level and are broadcast to the users.

(5) With some business models, the user can share in the network profits by installing a network reference station and getting a share of the subscription fees imposed upon other network users.

(6) Different formats and accuracies are readily available. GIS data, environmental resource data, mapping grade data, etc. can be collected with one or two foot accuracy while surveyors and engineers can access the network with centimeter level accuracy. RTCM, CMR+ and other binary formats can be user selected.

(7) The RTN can be quality checked and monitored in relation to the NSRS using NGS programs such as OPUS and TEQC from UNAVCO.

(8) Some systems have built-in integrity monitoring where baselines are computed and checked between the base station's known positions real-time.

Drawbacks to the user of an RTN compared to classical RTK positioning include:

(1) Network subscription fees. These may be prohibitive for small companies.

(2) Limited wireless data access.

(3) Interpolation issues. Network spacing, communication and error modeling must be handled optimally.

(4) Work outside the network envelope (extrapolation of corrections) degrades accuracy.

(5) The network solution may not fit to local control. Calibration may be necessary.

(6) Coordinate metadata. Is the network datum the user's required datum?

(7) User is subject to maintenance or outages, as when reliability operators exceed trigger thresholds that put the system offline at times that may be inconvenient to users.

NGS has an important role to play in this new positioning solution, both in providing support for these networks as well as protecting the public interest. In addition, NGS plans to encourage RTN to successfully align to the NSRS within a certain tolerance (to be determined) by connections to the CORS network. Following this document, NGS will develop user guidelines and administrative guidelines for RTNs in an effort to keep the produced positions homogenous and accurate for all levels of geospatial professionals. (above section directly excerpted from http://www.ngs.noaa.gov/PUBS_LIB/NGSRealTimeUserGuidelines.v1.1.pdf)

Table 5-1. Carrier Phase Tracking Techniques

| Concept | Accuracy | Minimum Requirements | Applications |
|---|---|---|---|
| Static (Post-processed) | Sub-cm | L1 or L1/L2 GPS receiver<br>30 min to 1 hour minimum observation time | Control surveys (high-accuracy)<br>Slow point positioning |
| Rapid Static (Post-processed) | Sub-cm | L1/L2 GPS receiver<br>5-20 min observation time<br>Single occupation only<br>No continuous satellite lock required | Control surveys (medium to high accuracy) |
| Stop-and-Go Kinematic (Post-processed) positioning | cm + | L1 GPS receiver<br>Initialization required<br>1-2 minute baseline occupation<br>Continuous satellite lock required | Control surveys (Medium accuracy)<br>Fast point |

Table 5-1 Continued on next page

Table 5-1. Carrier Phase Tracking Techniques (continued)

| Concept | Accuracy | Minimum Requirements | Applications |
|---|---|---|---|
| Pseudo Kinematic<br>(Post-processed) | Few cm | L1 GPS receiver<br>5-10 minutes static observations<br>Double occupations required<br>between 1 and 4 hours<br>No initialization required<br>Loss of satellite lock permitted | Control surveys<br>(Medium accuracy) |
| Real-Time<br>Kinematic<br>(Real-time) | cm+ | L1/L2 GPS Receiver<br>Data-Link required<br>Baselines should be < 10 km<br>OTF initialization or<br>conventional initialization<br>Maintain satellite lock | Real-time hydro tides<br>and heave corrections<br>Location surveys<br>Photo control (ABGPS)<br>Real-time topo<br>Construction stake out<br>(Medium to high accuracy) |
| Real Time<br>Kinematic<br>(Post Process Infill)<br>(RTK PP Infill) | cm+ | L1/L2 GPS Receiver<br>Data Link Optional<br>Baselines should be < 10 km<br>OTF initialization or<br>conventional initialization<br>Maintain satellite lock<br>Can collect with SV's | Increased Accuracy<br>over standard RTK.<br>No real time data when<br>CMR corrections are<br>not received.<br>Alternative option when<br>radio link is not reliable. |
| Real-Time<br>Network<br>(Real-time) | cm + | L1/L2 GPS Receiver<br>Data-Link required<br>Baselines unlimited in network<br>OTF initialization, may<br>require site calibration<br>Maintain satellite lock | Real-time hydro tides<br>and heave corrections<br>Location surveys<br>Photo control (ABGPS)<br>Real-time topo<br>Construction stake out<br>(Medium to high accuracy) |

5-6. Real-time Kinematic (RTK) GPS. The basic practical concept for real-time kinematic GPS surveying was developed in the early 1980's by Ben Remondi of the National Geodetic Survey. In 1989, the Corps' Topographic Engineering Center (now the Army Geospatial Center) began development of algorithms to enable RTK observation of tides for hydrographic survey and dredge elevation corrections in offshore environments. Today, nearly all GPS receiver manufacturers provide RTK survey options for engineering, construction, and boundary surveying applications.

a. RTK equipment. A RTK carrier phase positioning system is very similar to code phase tracking technology described earlier. Two GPS receivers (reference and remote) are needed for RTK positioning. These receivers must meet the requirements to process real-time carrier phase tracking information. The user equipment on the ground, construction platform, survey vessel, or dredge typically consists of a geodetic-quality, dual-frequency, full wavelength L1/L2 tracking GPS receiver. The GPS reference station must be located over a known survey monument (a benchmark if precise elevation densification is being performed). The reference receiver must be capable of collecting both pseudorange and carrier phase data from the GPS satellites. A geodetic quality GPS antenna is required to minimize multipath. The receivers should be capable of at least a 1-sec update rate. The processor used at the reference station will compute the pseudorange and carrier phase corrections and format the data for the communications link. The corrections will be formatted for transmission to the remote user; from which accurate, georeferenced coordinates are determined in real-time. As in code phase applications, the user datum must be correlated with the reference station datum, including accounting for geoid undulations that may occur between the stations. For hydrographic and dredging applications, the position output for the helmsman is code phase tracking using pseudoranges (accurate at the meter level)--for vessel navigation in real-time. The decimeter-level carrier phase DGPS data will be used to compute the vessel position and/or antenna elevation. The antenna elevation must be related to the water surface and vessel draft in order to reference GPS time-tagged depth soundings. GPS elevation data must also be transformed to the local reference datum--e.g., Mean Lower Low Water, Low Water Reference Plane.

b. Communications link. The communications link for a real-time carrier phase positioning system differs from the code phase tracking DGPS system in the amount of data that has to be transmitted. The carrier phase positioning system may require a minimum data rate of 4800 baud, as compared to a baud rate of 300 for the code phase tracking DGPS system. This high data rate eliminates many of the low-frequency broadcast systems and limits the coverage area for high-frequency broadcast systems. VHF and UHF frequency communications systems are well suited for this data rate, as are satellite links. Frequency approval may be necessary for communication link broadcasts using a power source in excess of 1 watt. RTK is rarely used for surveys in excess of 20 km from the reference station.

c. TCP/IP data connection. Data communication, especially in regard to RTN solutions, may be done via wireless data modem, card or phone with a dynamic or static IP address, although static IP addresses provide a reliable connection and are the recommended communication link configuration. Code Division Multiple Access (CDMA) data modems and flash media modems require the user to subscribe to a wireless phone service, but this allows for use of the wireless service providers’ cell towers for internet connectivity to send and receive data over much longer distances than with UHF broadcasts. Cell phones and stand alone Subscriber Identity Module (SIM) cards in Global System for Mobile Communication (GSM) networks use similar methods as CDMA data modems to send data. Many current GNSS receivers have integrated communication modules.

5-7. <u>Differential GPS Error Sources</u>. The error sources encountered in the position determination using differential GPS positioning techniques are the same as those outlined for absolute/autonomous positioning in Chapter 4. However, many of the errors inherent in absolute/autonomous positioning are effectively minimized when differential code or carrier tracking techniques are employed--especially when short baseline distances are observed with high-quality dual-frequency receivers. The errors that are minimized or eliminated include:

Selective Availability (S/A). When S/A was activated prior to 2000, differential positioning techniques eliminated this intentionally induced error.
Ionospheric and Tropospheric Delays. When the reference and remote stations are close together, these atmospheric delays are effectively eliminated. However as the distance between the differential receivers increases, these difference in the delays can become significant. For example, USCG code tracking radiobeacon systems are fairly accurate out to about 150 km. Beyond that distance, differing atmospheric conditions add to the range errors. In some cases, localized weather patterns at even shorter distances can affect the code tracking measurements.

Ephemeris Error. Ephemeris errors are significantly reduced with differential techniques. Processing baseline data with a precise ephemeris will further reduce this error.

Satellite Clock Error. Compensated as long as both the reference and remote differential receivers use the same satellite clock correction data.

Table 5-2 shows the nominal range error budget for a differential code phase tracking system where the common error sources from the space and control segments have been eliminated.

Table 5-2. Error Budget for Differential Positioning Systems (Code Phase)

| Segment Source | Error | User Range Error Contributions (± meters) Near | Far(>350 km) |
|---|---|---|---|
| Space | Clock and NAV subsystem stability | 0.0 | 0.0 |
| | Predictability of SV perturbations | 0.0 | 0.0 |
| | Other | 1.0 | 1.0 |
| Control | Ephemeris prediction model implementation | 0.0 | 0.0 |
| | Other | 1.8 | 1.8 |
| User (P(Y)-Code | Ionospheric delay compensation | 0.0 | 4.5 |
| | Tropospheric delay compensation | 0.0 | 3.9 |
| | Receiver noise and resolution | 4.1 | 4.1 |
| | Multipath | 3.4 | 3.4 |
| | Other | 1.0 | 1.0 |
| UERE (95%) | | 5.8 | 8.3 |

Source: Table 10-1, (DoD 1996)

In addition to these error sources, the user must ensure that the receiver maintains lock on at least three satellites for 2-D positioning, four satellites for 3-D positioning, and five or more satellites when RTK methods are employed. In performing carrier phase GPS static surveys, if lock is not maintained, positional results may be degraded, resulting in incorrect formulations. When loss of lock occurs, a cycle slip (a discontinuity of an integer number of cycles in the measured carrier beat phase as recorded by the receiver) may occur. Sometimes, in static GPS control surveying, if the observation period is long enough, post-processing software may be able to average out loss of lock and cycle slips over the duration of the observation period and formulate positional results that are adequate. If this is not the case, reoccupation of the stations may be required. In all differential surveying techniques, if loss of lock does occur on some of the satellites, data processing can continue easily if a minimum of four satellites have been tracked. Generally, the more satellites tracked by the receiver, the more insensitive the receiver is to loss of lock. In general, cycle slips can be repaired.

5-8. Differential GPS Accuracies. There are two levels of accuracies obtainable from GPS using differential techniques. The first level is based on pseudorange code formulations, while the other is based on carrier phase formulations. All accuracy assessments are highly dependent on the type and quality of the GPS receivers used--see *Global Positioning System Standard Positioning Service Performance Standard* (DoD 2001).

a. Pseudorange code accuracies. Pseudorange formulations can be developed from either the C/A-code or the more precise P-code. Pseudorange accuracies are generally accepted to be 1 percent of the period between successive code epochs. Use of the P-code where successive epochs are 0.1 microsecond apart produces results that are around 1 % of 0.1 microsecond, or 1 ns. Multiplying this value by the speed of light gives a theoretical resultant range measurement of around 30 cm. If using pseudorange formulations with the C/A-code, one can expect results ten times less precise or a range measurement precision of around 2 to 3 m. (Note that the DoD only commits to providing a ≤ 6 m UERE; however, PPS Signal-in-Space UEREs have been consistently less than 2 m--see Chapter 4 and DoD 2001). Point positioning accuracy for a differential pseudorange formulated solution is generally found to be in the range of 0.5 m to 5 m at the 95% confidence level. Sub-meter accuracy is easily achievable if code tracking receiver distances are short, e.g., less than 50 km, and PDOP is < 5. As always, these accuracy estimates are largely dependent on the type of GPS receivers being used and the distance from the reference station.

b. Carrier phase formulations. Carrier phase formulations can be based on the L1, L2, or both carrier signals. Accuracies achievable using carrier phase measurements are generally accepted to be 1 % of the wavelength. Using the L1 frequency where the wavelength is around 19 cm, one can expect a theoretical resultant range measurement that is 1 % of 19 cm, or about 2 mm. The L2 carrier can only be used with receivers that employ cross-correlation, squaring, or some other technique to get around the effects of A/S. Some of the factors that enter into the error budget of a differential carrier phase solution are:

Distance between reference and remote station.
Receiver quality. Low-end, inexpensive hand-held or geodetic quality--usually directly related to receiver cost which can range from $100 to $20,000 or more.

Receiver signal processing methods.
Single or dual-frequency tracking. L1 C/A-code, L1 P-code, L2 P-code, and/or L2 Y-code.
Number of satellites the receiver can track. Varies from 1 to "all-in-view." Less expensive, hand-held receivers typically track only 8 satellites. Most high-end geodetic quality receivers can track up to 12 or 24 satellites. Some receivers also track GLONASS satellites.
Satellite tracking channels in receiver. Varies from 1 to 40--12 channels being typical.
Baseline reduction and analysis methods. Also relates to number of epochs observed or length of observation--e.g., 1-hour or 6-hour static baseline observation.
Real-time kinematic or post-processing solution.
Integer ambiguity solution techniques.
Antenna design.
Redundant observations. Redundant baseline observations and connections from different network points will improve the computed positional accuracy of a point when the observations are processed through standard geodetic network adjustment routines.

The final positional accuracy of a point (or the derived baseline vector between two points) determined using differential carrier phase GPS survey techniques is directly related to the geometric strength of the configuration of satellites observed during the survey session. GPS errors resulting from satellite configuration geometry can be expressed in terms of DOP (Dilution of Precision). Positional accuracy for a differential carrier phase baseline solution is generally found to be in the range of 1-10 mm. On extremely short baselines used for structural deformation monitoring surveys (i.e. less than 1,000 m) accuracies at the 1 mm level are typically observed. Elevation difference accuracies tend to be larger--around the 5 mm level over short baselines. Real-time dynamic GPS measurements have even larger accuracy estimates due to velocities of the moving platform.

c. Accuracy estimates for differential GPS systems. The resultant accuracy of a differential carrier phase baseline solution is widely variable and depends on the factors listed in the above paragraphs. In addition, accuracies are difficult to quantify, given the variety of GPS receivers. Many organizations have performed independent testing of GPS receivers; however, these tests are often dated and may not be representative of "real-world" observing conditions. Likewise, receiver manufacturer's claimed accuracies are subject to unknown observing conditions and caveats--often similar grade receivers have widely varying accuracy claims by different manufacturers. Typically, code tracking receivers report positional accuracies as 2-D horizontal RMS statistics. Carrier tracking accuracies are usually reported as a function of the baseline distance, which includes both a fixed quantity and a parts per million (ppm) ratio of the baseline length. Accuracy estimates can also be indirectly derived from the results of network adjustments or comparisons with higher-accuracy baselines. The general accuracy values shown in Table 5-3 below are based on such comparisons and are believed to be representative of the current technology. In some cases, resultant horizontal and vertical accuracies can only be estimated because there is no independent method to accurately verify the data, e.g., offshore sea level or tidal elevation measurements using RTK techniques.

Table 5-3. Nominal Positional or Baseline Accuracies for Differential Positioning Systems (Single baseline observation)

| GPS Receiver or Tracking System | Estimated Accuracy (95%) Code | Carrier |
|---|---|---|
| Low-cost resource grade receivers (L1 only) | | |
| Baselines < 100 km | 3 to 5 m | n/a |
| Geodetic-quality 24 channel, L1-L2 (Static long-term baseline observations) | | |
| Short baseline length (< 1 km) | 0.3 to 1 m | 2 mm ±1 ppm |
| Baseline length < 10 km | 0.3 to 1 m | 5 to 10 mm ±1 ppm |
| Baseline length < 100 km | 1 m | n/a |
| Baseline length < 500 km | > 1 m | n/a |
| USCG radiobeacon receivers | | |
| Short baseline length (< 1 km) | 0.3 to 1 m | n/a |
| Baseline length < 10 km | 0.3 to 1 m | n/a |
| Baseline length < 100 km | 1 to 2 m | n/a |
| Baseline length < 500 km | 3 to 10 m | n/a |
| World-wide wide-area networks with atmospheric modeling | 0.5 to 2 m | n/a |
| Real-time Kinematic Observations with Geodetic-quality receiver (baselines less than 10 km) | | |
| Horizontal position accuracy | n/a | 10 to 30 mm |
| Vertical accuracy | n/a | 30 to 100 mm |
| Adjusted positional accuracy using multiple CORS stations | | |
| Horizontal | n/a | 10-20 mm |
| Vertical | n/a | 100 mm |
| Real-time Kinematic offshore tidal & heave modeling | n/a | 100 mm |

5-9. Differential GPS Augmentation Systems. A number of differential GPS augmentation systems are available from both government and commercial sources. Most real-time augmentation systems are code tracking. However, more emphasis is being placed on developing accurate carrier tracking augmentation networks. The following material on Federal augmentation systems is extracted from the *2001 Federal Radio Navigation Plan* (FRP 2001). Description of some commercial augmentation systems is covered in later chapters. The *2008 Federal Radio Navigation Plan* (FRP 2008) may be downloaded from: http://www.navcen.uscg.gov/pdf/2008_Federal_Radionavigation_Plan.pdf

a. Maritime Differential GPS (MDGPS). The USCG Maritime DGPS Service provides terrain-penetrating medium-frequency signals, optimized for surface applications, for coastal coverage of the continental US, the Great Lakes, Puerto Rico, portions of Alaska and Hawaii, and portions of the Mississippi River Basin. Maritime DGPS uses fixed GPS reference stations that broadcast pseudorange corrections and provide GPS integrity information using radionavigation beacons. The Maritime DGPS Service provides radionavigation accuracy better than 10 meters (95% RMS) for US harbor entrance and approach areas. The system is operated to International Telecommunications Union and Radio Technical Commission for Maritime Services (RTCM) standards and has been implemented by more than 40 other maritime nations. The USCG declared FOC of the Maritime DGPS Service on March 15, 1999.

b. Nationwide Differential GPS (NDGPS). A Nationwide DGPS (NDGPS) Service has been established under the authority of Section 346 of the U.S. Department of Transportation (DOT) and Related Agencies Appropriation Act, 1998 PL 105-66 U.S.C. 301. This service is an expansion of the MDGPS to cover areas of the country where service from MDGPS is not available. On April 18, 2008, the DOT approved a decision to continue the inland component of the NDGPS. This service provides an accurate and uniform real-time differential GPS correction signal that covers the continental US and selected portions of Hawaii and Alaska, regardless of terrain, man made, and other surface obstructions (see http://www.navcen.uscg.gov/?pageName=ndgpsMain). This is achieved by using a terrain-penetrating medium-frequency signal optimized for surface application. This service, along with MDGPS, provides a highly reliable GPS integrity function to terrestrial and maritime users. NDGPS accuracy is specified to be 10 meters or better. Typical system performance is better than 1 m in the vicinity of the broadcast site. Achievable accuracy degrades at an approximate rate of 1 m for each 150 km distance from the broadcast site. When each site is brought online, it meets all FOC requirements as set forth by the USCG for their MDGPS service. This includes integrity, availability, and accuracy. The NDGPS Service will achieve FOC when it provides dual coverage of the continental US and selected portions of Hawaii and Alaska with single coverage elsewhere. . The service is operated to the RTCM SC-104 broadcast standard. This standard has also been adopted by the international community as ITU-R 823 and has been implemented in over 40 countries, maritime and non-maritime, worldwide.

c. FAA Wide Area Augmentation System (WAAS). The FAA is developing the WAAS to augment GPS. WAAS is designed primarily for aviation users. The WAAS provides a signal-in-space to enable WAAS users to navigate the en route through precision approach phases of flight. The signal-in-space provides three services: (1) integrity data on GPS and Geostationary Earth Orbit (GEO) satellites, (2) differential corrections of GPS and GEO satellites to improve accuracy, and (3) a ranging capability to improve availability and continuity. The FAA announced in August 2000 that WAAS is continuously broadcasting differential corrections and is available for non-safety applications. WAAS initial operational capability for safety applications (as a supplemental means of navigation), supports en route through approach with vertical guidance operations. The long-term plans for navigation architecture are based on a WAAS primary means of navigation determination in 2009. To that end, as well as to improve performance, a key recommendation is to utilize the new GPS civil signal at L5 (1176.45 MHz) when it is available to provide a more robust, interference resistant, and available service to users equipped with L5 receivers. The result of these incremental improvements will enable aircraft equipped with WAAS avionics to execute all phases of flight except Category II and III precision approaches.

d. FAA Local Area Augmentation System (LAAS). LAAS augments GPS by providing differential corrections to users via a VHF data broadcast. Suitably equipped aircraft will be able to conduct precision approaches at airfields where LAAS Category I ground facilities are installed. LAAS will be implemented initially as a CAT I precision approach landing system. Prototype LAAS stations are installed in the U.S. in Memphis, Atlantic City, Cedar Rapids, Minneapolis, Chicago, Seattle, Moses Lake and Guam. In addition, a new LAAS facility will be installed in Newark in 2009. LAAS CAT I stations will be installed under FAR Part 171 as non-Federal systems. LAAS CAT II/III requirements definition and international harmonization are in progress. The decision on FAA's LAAS CAT II/III acquisition plans is scheduled for 2012.

e. The National Continuously Operating Reference Station (CORS) System. The National Geodetic Survey continues to expand its national CORS system to support non-navigation, post-processing applications of GPS. The national CORS system provides code range and carrier phase data from a nationwide network of GPS stations for access by the Internet. As of May 2010, the CORS network contains over 1,450 stations, contributed by over 200 different organizations, and the network continues to expand.