Chapter 8
Monitoring Structural Deformations Using the Global Positioning System

8-1. Purpose

This chapter provides technical guidance on the use of the Global Positioning System (GPS) for monitoring and measuring three-dimensional (3D) displacements on large engineering structures. Applications of GPS for the determination of long-term stability and movement on dams, navigation locks, and other similar types of construction projects are described. Technical guidance on procedures, standards, and specifications recommended for data collection and analysis are included.

8-2. Background

The specialized surveying practices described in previous chapters tend to be time and labor intensive. GPS surveying techniques for structural monitoring have a high potential for reduction in manpower needed for conducting deformation surveys. Although GPS can yield positions that are comparable to (and may even exceed) the accuracy levels expected for conventional surveys, its use in the past was limited because of a requirement for lengthy station occupation times. Reduced occupation times have now been realized through the use of specialized instrumentation and enhanced software analysis, resulting in reliable sub-centimeter accuracy from much shorter observing sessions. The technical guidance presented in this chapter contains the procedures and standards for the use of GPS measurements on deformation monitoring projects.

a. GPS overview. The GPS is a satellite-based positioning and navigation service used to obtain geodetic coordinates at a user location in the 1984 World Geodetic System (WGS84). GPS also has the capability for obtaining precise carrier phase measurements for relative positioning between two survey stations. Positional accuracy requirements on the order of 5 mm (horizontal and vertical) at the 95% confidence level can be reliably met using GPS technology, with certain limitations. Station occupation times can be reduced to approximately 15-30 minutes per station. Specialized receiver-antenna equipment adequate for use on monitoring surveys is widely available as commercial off-the-shelf products. GPS observation data can be converted to Receiver Independent Exchange (RINEX) format. RINEX is a universal means to store GPS raw data and orbit ephemeris files. Multiple GPS receiver units can be deployed and operated for many hours to conduct monitoring project surveys. Processing outputs and collected data supply high reliability and statistical assessments routinely applicable to network adjustment position determination. Simultaneous positioning can be obtained on stations normally configured for conventional surveying operations. No highly specialized data collection requirements are needed; however, data processing can become technically complex in more advanced applications of data filtering and data cleaning.

b. GPS applications and precautions. With further refinement of the data processing strategies presented in this chapter, lower cost and better performance on monitoring surveys could be expected from current GPS technology. At the present time, GPS surveying can be used to substitute for conventional monitoring techniques using the standards presented in this chapter. Attention to actual GPS data quality and prevention of systematic biases in the measurements must be made to ensure adequate results. GPS signal disturbances can be unavoidable under certain field conditions. Appropriate measures must be taken to obtain clean (unbiased) GPS data through mission planning, reconnaissance, and careful data post-processing and evaluation of the results. GPS is highly recommended for conducting surveys of the reference network of stable points surrounding the project structure. With high accuracy coordinates on at least two reference stations, and reasonably clean GPS data collected at monitoring points, high accuracy relative positioning can be routinely achieved. GPS users must take special care to minimize signal obstructions at sites that are prone to generating multipath signal reflections. Methods for accomplishing this are presented in this chapter.

8-3. Scope of Chapter

This chapter is divided into four sections, as summarized below.

Section I: Monitoring Structural Deformations with GPS. This section presents practical guidance for GPS monitoring survey operations. Surveying requirements for accuracy, system performance, and equipment are discussed. Surveying procedures and specifications for planning, fieldwork, and data collection are covered. Data processing procedures are covered which describe the software and processing requirements for baselines and networks, including least squares adjustment techniques. GPS monitoring applications included in this section cover planning surveys for reconnaissance, and criteria for the installation of GPS monitoring networks. Also included are procedures for performing reference network surveys that are conducted for separate high accuracy positioning tasks, and production surveys configured to follow conventional survey procedures and layouts. In addition, procedures for performing specialized GPS surveys are described--as may be required for continuous monitoring, or monitoring under hazardous conditions.

Section II: GPS Performance on Monitoring Networks. This section presents results of field tests conducted to evaluate GPS surveying capabilities on monitoring networks. Principles of GPS carrier phase measurements are summarized, including operational components and user survey controls. GPS receiving system performance, including random and systematic error sources, are discussed. Sources of error in GPS measurements are described relative to GPS system status and site specific effects that present major problems over short baseline networks. Examples are included of GPS performance in actual USACE project monitoring cases, which demonstrate comparable results to conventional surveys.

Section III: Data Quality Assessment for Precise GPS Surveying. This section presents examples and techniques for describing problems with GPS data quality in monitoring applications. Quality assessment tools, including statistics and quality control software, are discussed. Data post-processing, software, and statistics used to solve for baseline position components and evaluate results are described. This section also demonstrates how external network quality can be determined by closure and station checks using multiple inter-connected baselines.

Section IV: Mitigation of Multipath Signals. This section presents information for minimizing and removing multipath errors, which are a major source of systematic error in precise short baseline surveys. A description of multipath effects on GPS carrier signals is discussed. Possible techniques for data cleaning and data re-processing are presented, as are data filtering techniques that can be used to minimize errors and improve solution quality. Also covered are tests on using signal strength values for carrier phase measurement weighting that indicate improvements in removing bias and more robust ambiguity resolution.

Section I
Monitoring Structural Deformation with GPS

8-4. Surveying Requirements

a. Accuracy requirements. Typical accuracy requirements for PICES surveys range between 10 mm horizontally and 2 mm vertically for concrete structures, and up to 30 mm horizontally and 15 mm vertically for embankment structures--see Table 2-1. Surveying accuracy specifications are meant to ensure detection of a given amount of movement under normal operating conditions. Allowable survey error thresholds are related to the maximum expected displacement that would occur between repeated measurement campaigns. For each survey, final positioning accuracies at the 95% probability level should be less than or equal to one-fourth (0.25) of the predicted displacement value. In addition to the maximum displacement criteria stated above, the expected velocity and/or frequency (cyclic behavior) should be considered as a further practical basis for the design of accuracy requirements. Specification of accuracy requirements is a major factor in the evaluation of performance for a given GPS-based measurement scheme.

(1) Concrete structures. Long-term movement studies on large concrete structures (mass gravity dams) indicate that normal maximum relative horizontal deflections between any two monolith pairs are on the order of 20-30 mm, due mainly to cyclic-seasonal temperature and pool elevation changes. This implies an accuracy of 5-7 mm in relative horizontal positioning from each survey is required at the 95% confidence level, which is slightly less than the published standard.

(2) Embankment structures. Settlement of earth and rockfill embankments decreases as a function of time (due to consolidation). Normal vertical subsidence is on the order of 400 mm over a 5-10 year stabilizing phase, progressing most actively in the first two years. Mean settlement rates of approximately 50 mm/yr, up to a maximum of 140 mm/yr are typical. Horizontal displacements on embankment structures follow similar stabilizing trends with maximum displacements on the order 90-100 mm, occurring at peak rates of 30 mm/yr. Positioning accuracies of approximately 10 mm/yr vertically and 5-10 mm/yr horizontally are required at the 95% confidence level.

(3) Navigation locks. Navigation lock structures are subject to foundation uplift pressures (especially when dewatered for repairs), and progressive deterioration from use, age, and river environment effects. Lock monitoring includes events such as, ground motion due to nearby seismic activity, scour and associated wall settlements, and inward rotation of wall monoliths away from retaining embankments. Relative movement (tilt) on the order of 20 mm or less between the base and top walls would approach minimum safety and stability thresholds. Survey accuracies on the order of 2-3 mm are required to observe movement trends and give adequate warning time to evacuate the lock chamber(s) before failure.

b. System requirements. A successful GPS-based deformation measurement system must meet the following performance requirements:

(1) The system should provide relative horizontal and vertical positioning accuracies comparable to those obtained from existing conventional deformation surveys, within stated accuracy requirements of approximately 5 mm or less at the 95% confidence level.

(2) Station occupation times should be reduced to minutes per station, approximately the amount of time required for completion of a typical monitoring survey in one working day.

(3) The system must operate with commercial off-the-shelf (COTS) equipment having nominal power requirements, such as the geodetic quality GPS equipment and computers available from commercial sources. It is desired that the system not require classified access for full performance.

(4) The system must collect data that conforms to Receiver Independent Exchange (RINEX) standards for subsequent data post-processing. Raw GPS data logging capability must extend over a full eight hours for multiple reference stations.

(5) The system must provide redundant observations of monitoring point positions so that reliability, statistical assessments, and detection of outliers are enabled. Applicable GPS positions, baselines, and measurement weights must be compatible with requirements for geodetic network adjustment processing.

(6) The system must provide localized coverage over a network of survey points that would be typically installed on project sites. The system should be capable of simultaneously positioning multiple receivers/users on the structure.

(7) It is desired that no specialized operational procedures be required to initialize the system and conduct a mission. Any needed pre-mission operations must be within the capability of the survey crew to perform.

c. Equipment requirements. Only precise carrier phase relative positioning techniques will yield accuracies sufficient for GPS structural deformation surveys. Commercial off-the-shelf (COTS) geodetic type receiver/antenna equipment has the operational capabilities necessary for collecting high-quality carrier phase data. An inventory of recommended components for such a system are as follows:

(1) Receiver. A geodetic quality GPS receiver must have: L1/L2 phase measurement capability, with at least a one second data logging rate; up-to-date receiver firmware version, and hardware boards that include any features available for high fidelity carrier tracking, and RF suppression in static surveying mode; minimum 3-10 megabyte internal raw data storage with a port connection enabled for logging to a laptop computer, data collector, or data communications system; and other accessories for protection and transport, such as carrying cases.

(2) Antenna. At minimum, the antenna must be a dual frequency GPS L1/L2 microstrip antenna with flat ground plane or choke ring, and type-matched to GPS receiver. Both L1/L2 antenna phase center offsets must be published within 1 mm as measured along the mechanical axis to the antenna reference base-plate. Standard antenna base attachment rod/bolt, with 5/8-inch-diameter, 11NC tooling, or other precision forced centered attachment system is required. Standard antenna-to-tribrach mounting adapters and Wild-type tribrachs may be used as a forced centering assembly.

(3) Transmission cables. Antenna-receiver, and data communications (RS-232 serial port interface, or special), connector cables with maximum length of 35 ft. (or suitable number of line amplifiers to prevent degradation of signal and noise amplifying losses) are required.

(4) Power supply. Power supply (AC/UPS) and/or 12V DC battery power (gel cell, camcorder) with compatible charger units and cables. System needs to operate for 10 hours or more without recharge, therefore power requirement design must include peripheral device load. For example, a 12V DC 80 (+) amp deep-cycle marine battery, protective case, and cigarette lighter adapter cable for PC.

(5) Software. Data downloading, logging, or processing software needed for retrieving raw data files, and/or for communication with an external computer and/or other permanent data storage media.

(6) Computer. Computer equipment should consist of at least a 486 PC type computer and operating system having: 9-pin RS 232 serial and 25-pin parallel port interface connections; minimum 200 megabyte hard disk; internal battery and external power port; 12V DC power inverter with external power port connector; external tape/disk drive with PC connector cables and software; and multiple external disks with large (100 MB) storage capacity.

(7) Field equipment. Miscellaneous equipment may include: steel tape or rods for antenna height measurements, wide base opening tribrachs, and nadir plummet for precise tribrach centering; stable surveyors tripod; meteorological instruments; field book; and ground tarp.

(8) Post-processing software. GPS survey data and baseline processing software with RINEX conversion capability.

For multiple equipment systems deployed on a project, efforts should be made to replicate each unit as closely as possible. This includes specifications for hardware manufacturer, model, and physical specifications (e.g., cable lengths), firmware version, and software. Variations in measurement performance between different receiver-antenna system are reduced because equipment related biases are common to each system.

8-5. Surveying Procedures

a. Background. The objective of deformation surveys is to determine the position of object points on the monitored structure. Horizontal and vertical positions are now usually determined by conventional surveying instruments (e.g., EDM, theodolite or total station). Conventional surveys are established from a network of reference stations in stable areas nearby the project site. Distance, angle, and height difference measurements are made to object points on the structure. Work procedures consist of moving equipment from point-to-point and observing, recording, and checking field data on-site. Field data collection is designed for high-reliability by making repeated observations, obtaining check loop closures, conducting instrument calibrations, and collecting auxiliary data (if necessary). Extensive data processing is required to convert raw survey data into useful engineering values (via data cleaning, data reductions, final position determination, and displacement calculations). Final coordinates are based on a least squares adjustment of the survey observations using the fixed coordinates of the reference network. Position differences are observed over time at each object point. These define a specific displacement field valid for the time span between two surveys. The total set of point displacements are modeled as a geometric surface that analytically represents changes in the location, shape, and size of the structure (or its components). Deformation model parameters (linear strain, differential or block rotation, and translations) are used to solve for deformations at any desired part of the structure. The sensitivity and significance of these parameters depend on the number, spacing, and accuracy of the surveyed point positions.

b. GPS deformation surveys. GPS has several advantages over conventional surveys. It provides flexibility in the location of monitoring stations, semi-automated data collection and processing, reliable 3D positioning between two points, built-in error analysis and export capability for survey adjustments, and potentially faster hands-off field survey operation. The fieldwork and procedures for GPS deformation surveys can be conducted in ways that are very similar to conventional surveying field operations described in earlier chapters of this manual. Following is a discussion of recommended procedures for conducting GPS deformation surveys, including preparation, fieldwork, processing, and monitoring applications.

c. Preparation for fieldwork. Data collection efforts with GPS equipment require a moderate level of planning and coordination.

(1) Mission planning. Typically a GPS monitoring survey will require occupations of multiple station points. If multiple receiver units are employed, then coordination of different occupation sequences should be specified prior to the fieldwork. The schedule of station occupation times is based on GPS mission planning. Satellite constellation status and local observing conditions are determined from two main sources of information: (1) GPS mission planning software and, (2) Notice Advisory to NAVSTAR Users (NANU) bulletins. Both should be consulted prior to performing fieldwork.

(a) Mission planning. Software is used to predict the number of visible satellites, DOP values, the location of each satellite (azimuth and elevation above horizon), and continuous coverage for each SV over a given time period. The user must supply a recent GPS satellite ephemeris file and specify the time and geographic location of interest.

(b) Notice Advisory to NAVSTAR Users (NANU). GPS constellation status information is reported by announcements known as Notice Advisory to NAVSTAR Users (NANU). The US Air Force Space Command Master Control Station distributes NANU messages as frequently as new information becomes available. Automated Data Services (ADS) can be checked daily for current outages and scheduled events through the US Naval Observatory (USNO) Internet link at: http://tycho.usno.navy.mil. ADS NANU message contents will either describe any warning conditions or indicate nominal operation of the satellite constellation. NANU message files and archived messages are obtained from U.S. Coast Guard Navigation Center (NAVCEN) at: http://www.navcen.uscg.mil. The information contained in the archived NANU files include the NANU message number, relevant start and stop date referred to the Day of Year (DOY) that begins at 0000 UT, Message Type (Forecast Outages, Unscheduled Outages, Other), Space Vehicle (SV) and code (PRN), reported Condition, and POC for further information. Standardized message types are designated by abbreviations that describe the condition being reported. NANU bulletins should be checked in advance of and after completion for the times scheduled to conduct GPS monitoring surveys.

(2) GPS equipment. Sufficient time must be budgeted to assemble and organize GPS surveying equipment for transport and/or shipping to the project site immediately prior to the scheduled work. Access to project AC power may require coordination with on-site personnel and all portable DC battery units must be fully pre-charged. A standard property inventory or packing list should be prepared to ensure all necessary equipment is available. Maintenance and inspection of this inventory should be completed before and after each monitoring survey. Items to check include: the condition of exposed parts of the receiver system and accessories, cables and connectors, spare cables, tribrachs and tripods or forced centering brackets, and any loose or missing mechanical parts. Electronics (GPS receiver) and/or computer data storage systems need to be cleaned of any obsolete session files, and then tested for cold start power up/down. All items should be packed and transported in protective cases as appropriate.

d. Fieldwork procedures. Data collection efforts depend on consistent fieldwork practices. The recommended sequence of events for each monitoring station occupation is as follows.

(1) Preparation. Setup tripod, forced centering device, or other stable antenna-mounting frame over monitoring point at station mark. Attach tribrach/trivet assembly, level, and precisely center over reference mark to within 1 mm accuracy. Insert antenna mount adapter into antenna base plate and secure, then place antenna/adapter into tribrach/trivet receptor assembly and orient the direction of the antenna. Attach antenna cable to antenna port and feed it to the corresponding receiver data port plug. Connect 12V DC power supply to the receiver unit power port using battery power cable, or through

extension cord, power inverter (e.g., 300W), and receiver power cables when using AC power supply. Power up receiver unit to begin satellite acquisition search.

(2) Receiver user-defined parameters. Mask angle is set to zero (0) degrees, PDOP cutoff is set to 20 or higher, data logging rate is set to one (1) second, power port control is set to enable primary external battery, P (Y)-code tracking is disabled, and data type is set to normal (full) data collection.

(3) Station data logging. Antenna heights are measured twice to within less than 1 mm and recorded on station data sheet. The antenna ground plane is oriented to magnetic/true north, and secured. Once the receiver unit has acquired at least five satellites (L1/L2 tracking), the survey session can begin. Initiate data logging using the appropriate user controls. Filename and antenna heights are entered in the field through the user interface keyboard. Filenames should reflect station names and antenna heights are designated as vertical or slant range to the ground plane.

(4) At the end of the station observing session, the data logging function is terminated through the user interface and the receiver unit is powered off. Antenna heights should be re-checked. Equipment is disassembled and transported to the next station setup.

e. Data collection procedures. The following data collection scheme may be used at each station to conduct the monitoring survey.

(1) Session length. A session length of 15-30 minutes (L1/L2 GPS carrier phase data) is required to meet minimum positioning accuracies using two simultaneously observed reference stations. On stations where unfavorable signal quality is expected, session lengths may need to be increased based on the outcome of reconnaissance surveys.

(2) Redundancy. Stations are positioned relative to at least two stable reference stations in the reference network. Simultaneous data collection at all three stations is required. Greater redundancy can be obtained by observing each station twice at different time periods. This ensures that the satellite constellation has changed over a significant time period (1-2 hours minimum).

(3) Coverage. A minimum of five (5) visible satellites must be tracked at all times--preferably five or more satellites will have continuous tracking throughout the session. GPS mission planning software should be used to maximize the number of continuously tracked satellites in each session.

(4) GPS data types. At a minimum, L1 phase and C/A code data must be recorded by the receiver at specified logging rates. Dual frequency data should be collected where possible to enable data quality checks and to provide additional GPS observations that enhance survey reliability.

(5) Station data. Specific information related to the data collection must be noted and recorded on the appropriate log sheets. These include: station name, L1/L2 phase center offsets (m), receiver and antenna serial numbers, observer name, date of survey, start and stop times of each session, notes about problems encountered, entered filename and antenna height, antenna cable lengths (m), and session number if occupation is repeated.

(6) Recording interval. A one (1) second data logging rate should be used in all data collected for monitoring surveys. The logging rate is defined as the time interval (in seconds) between each data value recorded in the receiver's internal memory or written to an external storage device. This can produce very large data files that can overload even very fast CPUs if processed as recorded. Some file editing to window the data into manageable pieces is possible once full processing for reference station coordinates has been completed.

8-6. Data Processing Procedures

a. General. Guidance for processing raw data is designed to meet the accuracy requirements set out on paragraph 8-4 (Surveying Requirements). A variety of software applications are available for GPS data post-processing and adjustment. Commercial software is adequate for most GPS monitoring surveys, with some limitations. Scientific versions are more complex and may require auxiliary data to enable certain user-functions. These higher-end packages are capable of extensive and customized processing with robust levels of output and statistics. Recommended procedures for GPS data post-processing on monitoring surveys are summarized below. Background on data processing mechanics is presented in Section III of this chapter.

b. Software requirements. Most GPS post-processing software has standard features for loading data and processing baselines. This is because different applications generally have the same requirements for internal treatments of GPS data and computations. Capabilities for baseline processing software should include the following considerations. Both static and kinematic mode post-processing should be available using a standard session input data file (e.g., RINEX). Satellite data deletion and data editing should be available that is indexed by SV number or by session measurement (indexed by time epoch). A standard text editor or user-developed software programs should be available for measurement editing in the RINEX file. GPS L1 and L2 carrier phase measurement and C/A code position solutions should be available. The option for using only L1 signal or L2 signal data should be selectable for position solution output. RINEX data and ephemeris file input data should be enabled without any special problems. Extraction of ASCII format position data in X-Y-Z, Cartesian WGS84 coordinates, with subsequent conversion of solution data to WGS84 geodetic coordinates, and to projected nothing, easting, and vertical coordinates, should be available.

c. Raw GPS data. Information required for post-processing raw GPS observations and GPS ephemeris files are summarized below.

(1) Observation files. Raw data is downloaded from the GPS receiver and imported to the processing software using a computer. Data files stored in binary form must be translated to native data structures that are unique to each software. A universal standard for GPS data transfer is known as RINEX format. This is an ASCII text file format containing a header section followed by time tags with blocks of GPS observations listed under each time tag--refer to Section III.

(2) Ephemeris files. Orbit data is broadcast in real-time (by the GPS satellite) in the GPS signal navigation message. An ephemeris file stored by the receiver contains the decoded satellite orbit data. The broadcast ephemeris can be extracted from the raw GPS data file or is sometimes stored separately with a conventional file name extension (e.g. *.eph). A more refined orbit, known as the precise ephemeris, contains smoother, more accurate post-processed orbit data. A daily precise ephemeris is available over the Internet from the USCG NAVCEN website. Precise ephemeris files usually can be obtained in either binary (*.E18) or ASCII (*.SP3) format. Both may require the post-processing software to be able to interpret these formats. GPS ephemeris files are also produced and archived in RINEX format by university and scientific organizations.

d. Baseline processing. Processing steps for a single GPS baseline are outlined below.

(1) Baseline input data. Computation of baselines requires the following information supplied or edited by the user: station names specified for each endpoint of the baseline, antenna heights in meters for both baseline stations, separate filename for GPS data collected at each station, approximate coordinates

for each station with position quality, receiver and antenna type with known phase center offset, and session start and stop times for each station observation set.

(2) Baseline processor controls. Setup functions for baseline processing require the following control values supplied by the user. Fixed station WGS84 geodetic coordinates must be supplied for at least one occupied station. Accuracy at the fixed station should be close to the centimeter level for best results (e.g., ambiguity resolution). Generally, fixed station coordinates from initial GPS installation surveys or prior monitoring surveys can be used. Satellite elevation mask angle is set between 15-20 degrees. For poor quality data the mask angle may need to be increased (if selectable for each SV). An alternative is to directly edit the RINEX file to remove satellite data at user-selected low elevations, based on data quality assessment statistics or other criteria. GPS baselines are processed for L1 solution only, with the output log file option set to calculate residuals for each double difference combination that was used in processing. Double difference residuals will not be reported for at least one satellite throughout the processing session, as it will be fixed internally as a reference. Set the software to use both L1 and L2 phase and code data if available. This additional data is used by the software to improve ambiguity resolution. Select at least a 95 percent confidence level for reporting all statistical outputs and for measurement outlier detection. The software may supply a default statistical testing value that is equivalent to using a formal 95% confidence in the statistics. Both static and kinematic processing modes can be run using the same baseline processor settings without affecting the mean position solution. Select options for full information logging for each solution output file. Processor log files are typically created for both viewing and printing the baseline processing results. If there is a large amount of output data, printed log files may be easier to view than manually scrolling through it on the monitor.

(3) Evaluation of processing output. The results of each baseline solution are examined for completeness and then compared to survey design specifications. Acceptable mean and standard deviation of residuals are generally in the range of 3 mm and 4 mm respectively, with a fixed L1 phase only solution. Standard deviations of each X-Y-Z baseline component are less than 2.0 mm (one-sigma). Processing variance factor should be between 0.5 and 2.0, and the ratio of fixed to float RMS should be greater than seven (7). Distribution of all double difference residuals should pass the Chi-squared goodness of fit test at the 95 percent confidence level. Scaled point confidence ellipse major semi-axis should be less than 3-5 mm (95%) for each station. The baseline processor software must remove all cycle slips and measurement outliers in data.

e. Network processing requirements. The steps used for processing multiple baselines in a monitoring network are outlined below.

(1) Reference network. The reference network is processed before the monitoring network in order to establish high accuracy control coordinates for each reference station. All simultaneously observed baselines are processed separately between each reference station that was occupied during the survey. One station is selected as a master station having an averaged code position or transferred area control known in WGS84 Geodetic coordinates. These coordinates are established during network installation surveys. Control coordinates on the master station are held fixed in a minimally constrained network adjustment of all reference network baselines. Static session mode solutions are all that is generally required for processing the reference network baselines. Data and post processed results should be examined to remove any obviously poor data following session status and data editing criteria presented in Section III of this chapter. Input controls and output statistics listed above should be satisfied for all reference network baselines. If there are four or more reference stations, then stable point analysis can be applied to detect movements in the reference network. Processing outputs and edited data files are saved separately as part of the project data archive.

(2) Monitoring network. All stable reference network stations are fixed with control coordinates established by the reference network survey processing results. Each monitoring station data file is processed baseline-by-baseline using each simultaneously observed reference station data file. Input controls and output statistics listed above should be satisfied for all monitoring network baselines. Misclosures and data quality checks should be made for baseline post-processing involving each monitoring point following criteria presented above. Processing outputs and edited data files are saved separately as part of the project data archive. Solution files are prepared for export to network adjustment software. An initial adjustment using only minimal constraints can be run between the master reference station and all of the monitoring points to examine initial survey quality.

f. Network adjustment requirements. Once all of the data has been processed and validated, GPS baseline ties will connect the entire surveyed network of monitoring points. All post-processed GPS solution vectors are processed using least squares network adjustment software. Weights are usually supplied by the baseline processing covariance matrix of parameters. The resulting coordinates for each point in the monitoring network define the final 3D position of each monitoring station. Stable reference station coordinates are fixed in the project coordinate system. Standard network adjustment procedures and outputs are obtained for the GPS monitoring survey. At a minimum, error ellipses (95%) are compared to accuracy requirements, and residuals examined for systematic bias.

g. Position displacements. Final coordinates are differenced from the previous survey adjustment to determine the 3D displacement at each survey station. An examination of plotted movement trends (coordinate differences) and comparison of direction and magnitude to the maximum expected displacement is made to summarize deformations of the structure. Any unusual or unexpected movement trends should be traced back so that the supporting GPS data is validated a second time.

8-7. GPS Monitoring Applications

a. General. Various kinds of GPS project surveys are made to obtain specialized information about the structure and its surroundings. These can be classified into four different application types, namely: planning surveys, reference surveys, production surveys, and specialized surveys.

b. Planning surveys. Reconnaissance and installation surveys are made before implementing an extensive program for GPS monitoring. In most cases it will be necessary to collect information about site-specific GPS performance. This involves fieldwork and measurement tests conducted in the planning stages of the design to check proposed new or upgraded project monitoring systems.

(1) Reconnaissance surveys. After it has been established that GPS surveys are a strong candidate system for obtaining deformation measurements (based on job requirements), a site visit is required for reconnaissance. These surveys are made to determine possible locations for monitoring stations, to identify any site-specific data collection problems, and to estimate system installation and future operation/maintenance requirements.

(2) Station placement tests. The objective of the site visit is to collect GPS test data at locations where monitoring is requested (as specified in the monitoring plan). A second objective is to establish temporary points within the area of interest where the best quality data can be obtained. The reconnaissance survey should reflect the proposed permanent survey system as closely as possible using only enough points to check data quality. Baselines are observed at each major section of the structure, especially if site conditions change to where data may be suspect. As few as 2 to 3 baselines on the structure, and, at minimum, one session on each reference station should be observed. Session lengths should be at least one hour for each test station, and at least one baseline session on the structure should be greater than 3 hours. Once the data has been collected and processed, an analysis of its suitability at

each proposed location is made by data evaluation methods presented in Section III. If problems are encountered with a particular station, these will be relocated or be reported to the monitoring system designers for alternative placements.

(3) Example placements. Typical station placement tests might include: stations at the crest and toe of embankment structures; across the total length of the crest of concrete dams, with separate baseline ties to rock abutments made from at least one of the crest monoliths; for navigation locks, station ties from the bank area to the riverside wall, along the length of one wall, and in any areas where stations must be located near walls or obstructions. One test method is to use multiple GPS units deployed over a cross-section of 2 to 3 GPS monitoring points, with simultaneous logging on least one reference station. Most important is that all reference network stations should be occupied and observed for at least one session during reconnaissance surveys.

(4) Maximum baseline length. GPS baselines should not exceed 1 to 2 km from the furthest reference station, if possible. Better results are obtained if only hundreds of meter distances separate the stations. A test should be made over the maximum length baseline on the project to determine the expected low-end precision for the surveys. The GPS baseline length test is at least 3 hours in duration to ensure the solution converges to a stable accuracy level. Baseline accuracy can be examined to determine if the test results meet specifications set out in Section III.

(5) Multipath detection tests. Baseline results and statistics are examined according to methods presented in Section III and IV--to detect the presence of multipath error.

(6) Receiver signal tests. Two GPS stations located near each other on the structure--say within 10 meters--allow both receivers to collect data that should be nearly identical. Data processing results can verify signal error levels where there are large nearby obstructions (several meters away) or vertical walls extending above the antenna.

(7) Mission planning. Reconnaissance surveys can verify mission planning results through comparison with actual GPS data. Data types such as, number of satellites, continuous coverage, DOP values, elevation angles, and visibility windows for specific satellites are examined to confirm design values. Any potential trouble spots in the observing area should be identified before making permanent station installations.

c. Installation surveys. After permanent monitoring stations are selected (and monumented) an initial GPS network survey must be made to complete the installation. This procedure involves a site visit with all field equipment required to conduct the installation survey. The initial survey of project baselines should be made to higher standards than those designed for production monitoring. Additional GPS data will yield high accuracy initial positions and supply a relatively large amount of data for a final system performance checkout. The surveying methods used for the initial survey of the reference network are identical to those used for production work. Data collected at each of the monitoring points on the structure may have 25-50 percent longer sessions, or at least one hour of data (whichever is greater).

d. Reference network surveys. The reference network consists of stable monuments set near the structure as a permanent reference frame for tracking movement of the structure. Surveys of the reference network require the highest accuracy measurements on monitoring projects. The precise relative position of each station in the reference network is needed to produce better accuracy during production surveys. The following design specifications for reference network surveys are recommended.

(1) Number of stations. A minimum of two reference stations must be occupied during the entire data collection phase of the production surveys. Three or four stations may be required if the project site

has difficult station placements (due to terrain, sky visibility, long baselines) or special high position reliability requirements. At least one (preferably two) continuously occupied control points on the structure (tied into the reference network surveys) will allow short baselines to be observed to the monitoring points.

(2) Session length. At least 3-4 hours continuous occupation time at each reference station is required. More than 4 hours will improve the reliability of the positioning. Reference station surveys are conducted at the same time as production surveys. Data editing for reference surveys is less critical than for production surveys because there is usually a larger percentage high accuracy data. A reasonably clean data set must be obtained for the reference network but this is not usually a problem because observations are made over much longer sessions.

(3) Visibility. Wide-open areas with sky visibility in the south direction are preferred. Large objects (buildings, walls, fence lines) in the vicinity of the station should not extend above the antenna ground plane if possible. Areas free of any obstructions that produce signal reflections (e.g., buildings, water bodies, and metal structures) are most favorable. Sometimes tourist overlooks and open areas near parking or picnic facilities can provide the best locations for reference stations on reservoir projects.

(4) Structure reference points. It is recommended that at least one control point station be placed on the structure itself. With this structure (reference) point scheme there will always be a high-order station at a short distance to the monitoring points. The structure station is tied into the surrounding permanent reference network using long observation GPS baseline data. The longer observing session provides better positioning accuracy and better ambiguity resolution to the monitoring points.

(5) Station occupation. Reference stations should be constructed and maintained according to guidance presented in previous chapters. Antennas should be force-centered to within 1 mm tolerance. Antenna heights should be no less than 1.5 meters from the ground. Obstructions in the immediate area should be no closer than 1 meter to the antenna. Geodetic L1/L2 antennas with ground plane are required, and choke ring antennas can be used to improve multipath suppression.

(6) Project datum selection. Coordinates in the WGS84 system should be used to define the project datum if possible. Observing ties to NGS or other local high-order control networks can be used to establish initial coordinates on monitoring reference networks.

e. Production surveys. GPS production surveys share many practices with conventional surveying. For example, setting station monuments, occupying these stations, data processing and reductions, and archiving results. Advantages over conventional surveys include less reliance on station intervisibility, automatic data collection, semi-automatic data processing, electronic data transfer and storage, and flexibility in deployment. GPS techniques presented in this section attempt to match the work flow and field procedures familiar in conventional surveys as closely as possible. Processing production survey data includes both kinematic and static mode solutions. Kinematic mode allows the user to examine and edit positioning data within a series of discrete position solutions. Static processing provides adjustment residuals and robust session statistics. Results of both types of processing should be compared during the evaluation of the survey.

(1) Kinematic surveys. Kinematic positions are processed sequentially from the raw data to obtain an output at every measurement epoch, provided the integer ambiguity for each satellite is resolved. Kinematic processing involves downloading data from each receiver as would be done for a static session file and then either converting to RINEX or retaining as a binary file. Selecting the kinematic processing option will force a solution in kinematic mode. All other processing options are set as if it were a static session. One reference station is held fixed with its high accuracy coordinates. Next,

process the L1/L2 data for each two-station baseline and extract the time series of WGS84 X-Y-Z positions for the monitored point as an ASCII file. Export the data in columns to a spreadsheet or similar software package. Various statistics can be computed such as a mean value for each coordinate component (X, Y, and Z), point differences from the mean, and plotting the position deviation time series. Problem data is identified by inspection and testing according to the quality control procedures in Section III. Clean data is separated by selecting time epochs associated with the best data quality statistics and then reported or re-processed. An average of the highest quality kinematic positions is made to obtain the final position for the monitored point with respect to the reference station.

(2) Static session processing. Data collected in static survey mode is processed as a block to produce an average position over a given time span. This has the advantage of providing a high degree of redundancy over the entire GPS observing session. Interpretation of statistical outputs is simplified when using a static session mode; however, biases can more easily corrupt the processing session as a whole. Static surveys work best at stations where GPS data has been confirmed to be of high quality, such as where the observing conditions are historically very favorable.

f. Specialized surveys. GPS can be used for continuous deformation monitoring as a permanent installation, during temporary repair work, or where human occupations are potentially hazardous.

(1) Continuous monitoring systems. GPS can produce real-time continuous positioning for monitoring applications. The main practical drawback is the high cost associated with permanently installing multiple receiver units on the structure and the specialized software to process and display the desired outputs. Although equipment prices have lowered in recent years, deployment of more than a few systems on a structure can be cost prohibitive. Generally, continuous GPS monitoring is used for plate motion and tectonic studies that cover wide regional areas. For example, there is the seismic monitoring array in the western U.S., and the extensive global GPS tracking networks established by the International GPS Service for Geodynamics (IGS). Localized GPS networks have also been developed that track movements on structures in a continuous operating mode. These systems are configured for either static or real-time survey operations with a GPS receiver, antenna, data communications system, (e.g., radio-link, fiber-optic line), and a power supply. A single off-site GPS base station is used to assemble and process outputs from multiple GPS units mounted on the structure. Communications to the base station are through spread spectrum radio and may broadcast either raw data, data corrections, or positions, depending on the processing configuration. Batteries are used as either a primary or backup power supply. With adequate power and receiver system protection, these units are designed to operate continuously for extended periods of time. Problem situations and data corruptions can arise in continuous operation--for example, occasional abnormal GPS satellite status, extreme weather, equipment failure, accidents, bird nesting on antennas, and power interruptions. Software required to process continuous GPS data will usually have to be specially developed to suit the proposed equipment, data types, and desired outputs. One of the advantages of continuous monitoring systems is their ability to collect data over very long sessions that can be processed and archived as daily session files. Millimeter accuracies are typical for daily GPS sessions collected over relatively short baselines. Another advantage to continuous GPS monitoring is the ability to customize outputs, such as for high accuracy, increased sensitivity to movement in a particular direction, or to warn the user if movement exceeds a safety threshold.

(2) Hazardous conditions. Conventional GPS surveys can be used in situations where the structure is undergoing repairs. In hazardous conditions, GPS can be set up to log continuously in kinematic solution mode to provide near-instantaneous movement data to site personnel. Usually these surveys are a temporary source of movement data. A typical configuration is with a GPS rover and a base station providing continuous real-time position output. Each system is equipped with communications to enable monitoring at a safe distance while providing the same outputs as conventional GPS monitoring.

8-8. GPS Survey Reporting and Results

a. General. This paragraph describes survey reporting, data organization, and permanent storage of GPS data and results.

b. Survey reporting. GPS monitoring surveys produce large amounts of data and processing outputs. Some of this information is critical to examine and save--other parts are not valuable or are not required for the overall objectives of the survey. Important types of information include the final position outputs from the least squares network adjustment. This includes a numerical summary in the form of tables for the previous and current surveys. Graphs, charts, and diagrams that document the performance of the survey at each monitoring station are useful as supporting data. For example, condensed tables of processing results, statistics, kinematic positioning plots, displacement trends, and reference network survey reports each as a separate appendix. Statistics should provide survey point positioning error reports for each station at the 95 percent confidence level. Plots of station error ellipses in their respective locations (site plan) help visualize the final survey quality. Sessions that undergo any specific data editing or have specific data quality problems can be placed in a separate appendix. Reporting formats should follow practices established for conventional monitoring surveys.

c. GPS data storage. Monitoring survey data and results must be archived for future reference and possible use. Raw data files, processing outputs, and final results should be maintained in electronic form for data compression. Raw data should be converted to RINEX and stored along with ephemeris data as a separate data directory. Generally, information will be stored in sub-directories according to the project name, survey campaign, and by date it was collected or processed. Most GPS processing software provides an option to archive the entire survey in a single compressed file. Precautions must be taken against the processing software (version) eventually going out of date where archived project files can not be retrieved. Enough information should be saved to reconstruct the final results from each survey using a non-proprietary data archiving system. Custom processing outputs, such as edited output files, plots, and the final report should also be archived in a separate computer file and directory. An index to the project survey files is critical and should be placed in a 'readme' file that is easily accessible. For example, have all survey data in a separate directory, including raw data, ephemeris data, and any edited data files (annotated in the comment section to describe file edits). A separate directory is reserved for storing processed outputs such as the software-specific project archive, session log files containing error reports, and data quality indicators. A separate directory is reserved for the project network adjustment and its associated results and outputs. A separate directory is reserved for baseline processing solution files covering static mode sessions and any spreadsheets used to examine kinematic station position solutions. The recommended media for project archiving is write-once compact disk (CD). Generally, one CD for each completed monitoring survey will supply enough permanent data storage capacity and will keep all related survey data and results in one place.

Section II
GPS Performance on Monitoring Networks

8-9. Principles of GPS Carrier Phase Measurement

a. General. There are two different methods for positioning with GPS signals, namely: (1) code range and (2) carrier phase. Only GPS carrier phase is accurate enough to be used for monitoring surveys. Code ranges are described below only to complete and simplify the carrier phase discussion that follows.

b. Navigation message. A navigation data message, containing satellite and system information, is broadcast by each satellite to enable GPS code range positioning at the receiver. The 50 Hz navigation message is modulated onto each GPS carrier signal in 25 data frames each containing 1500 bits of data. Each frame is further divided into 300 bit sub-frames containing: satellite clock bias terms (offsets from GPS master clock); satellite health information; broadcast ephemeris (predicted satellite position in orbit as a function of time); almanac data (low precision clock and orbit data for all GPS satellites); constellation health and configuration; text messages; and GPS-UTC time offsets. The navigation message data stream is compiled into a separate block of data known as the ephemeris file. The GPS ephemeris file is required for data post-processing.

c. GPS code range. GPS satellites continuously transmit a spread spectrum signal composed of two binary phase-modulated (PM) pseudo random noise (PRN) codes called C/A code and P(Y) code, and a navigation data message (ephemeris). Transmitted RF signal power is diffused over a wide bandwidth to resist signal jamming and interference. Each GPS code output is controlled by a pre-defined chip sequence unique to each satellite at a given time, and are set to maintain low cross-correlation values (i.e., orthogonal). PRN codes follow binary phase shift key (BPSK) formulas with a known structure that allows the GPS receiver to generate an exact replica code sequence. Cross-correlation and tracking of the received PRN code recovers precise Space Vehicle (SV) timing data from an on-board atomic standard. Local receiver generated codes are synchronized to the transmitted code using delay lock loop (DLL) signal processor. Differences between received and internal code sequences are minimized during correlation and the active incremental time shifts that occur as a result of correlation matching are measured and recorded. Time differences are converted to a range value between the antenna and each GPS satellite. With at least four satellites being tracked, a unique intersection point is defined in relation to World Geodetic System 1984 (WGS84) coordinates. GPS code ranges provide an absolute point position that can be output in WGS84 geodetic coordinates. Code ranges do not provide high position accuracy in relation to the requirements for monitoring structural surveys. Code ranges are used in signal processing operations involving carrier phase data, such as initial signal acquisition, code stripping, and timing.

d. GPS carrier phase. GPS code and navigation data are modulated onto two separate L-band frequency (microwave) EM carrier transmission links (L1 and L2). The L1 frequency carrier has a 19.03 cm wavelength, and the L2 frequency carrier has a 24.42 cm wavelength. GPS carrier signals propagate as electro-magnetic waves; therefore, signal phase can be tracked in the receiver unit by the use of phase lock loop (PLL) circuits. Carrier phase measurements are the basis for high precision surveys for relative positioning. The L1/L2 phase states in two receivers are simultaneously tracked and recorded at regular epochs by each receiver. Data collected by the GPS receivers is then referenced to a common GPS time system, which is a requirement for later post-processing. The signal phase processed through each receiver channel is accumulated by counting the number of cycles and fractions of cycles that have registered over a given span of time under continuous cycle lock. Both the instantaneous phase difference and integer number of full wavelengths (integer ambiguity) between each satellite-receiver pair are known at each receiver station. Various linear combinations of the measured phase are processed in a least squares adjustment to compute coordinates differences between each station. These phase measurement combinations include single, double, and triple differences. The most important of these observables is the double difference phase. It has the desirable property of enabling the use of GPS carrier waves for precise ranging and for eliminating major sources of systematic error.

e. GPS operational components. Components of the receiver/antenna instrument assembly provide the operational capability to measure GPS carrier phase. GPS surveying equipment consists of antenna, coupling circuits, transmission line, and receiver unit. Performance of GPS equipment is highly dependent on the type of electronic, control, and signal processing components in the receiver unit and the manufacturing quality of the antenna element.

(1) Antenna. GPS microstrip antennas are manufactured to precise dimensions and tolerances to enable uniform signal reception. GPS antennas operate by generating an electrical response to an incoming EM signal with high sensitivity to signals arriving in the half-space above the antenna element. The antenna response is localized at the edges of the microstrip (patch) antenna board. The local EM field created by the signal waveform is sampled at the phase center of the antenna. An average position for the distributed field intensity is the best-fit center of phase for the antenna. This location is where the antenna senses the GPS signal and defines the positioning reference point in GPS surveying. Due to slight uncontrollable manufacturing defects, phase center position uniformity can vary between different antennas as a function of satellite elevation angle and azimuth.

(2) Pre-amplifier. The amount of RF power at a specific frequency is low for GPS spread spectrum signals. Usually it is embedded below thermal noise levels (-160 to -166 dB) before waveform correlation and de-spreading is used for carrier recovery. Input signals are amplified by low noise pre-amplifiers located at the base of the GPS antenna (this happens after RF interference bandpass filtering).

(3) Antenna cables. Coaxial transmission cables carry input signal voltages from the antenna pre-amp to the antenna port plug-in on the receiver casing. Cables are specially designed to have matched characteristic line impedance and VSWR transmit properties with respect to both the antenna and receiver terminals. Therefore, substitutions to standard cable equipment supplied by the manufacturer are not recommended.

(4) Signal converters. Downconverter frequency mixing lowers carrier input to an intermediate frequency (IF) where analog-to-digital (A/D) conversion and sideband filtering takes place.

(5) Receiver channels. Digital IF signals are input to receiver channels and combined with replica in-phase (I) and quadrature (Q), orthogonal sine/cosine carrier maps (periodic replica waveforms) generated by the receiver's internal reference oscillator. Code, data, and carrier stripping for each SV occurs in the receiver channel.

(6) Phase Lock Loop (PLL). Two signals are input to a PLL circuit, one external and one internal. The PLL is essentially a clock that adjusts its frequency (or phase) to match an input signal. PLL electronic control techniques maintain the phase of the internal (local) oscillator signal close to the phase of the external GPS signal to allow phase tracking. Components of the PLL circuit are the phase detector (comparator), loop filter, voltage controlled oscillator, and frequency divider.

(a) Phase detector. The phase detector produces an output voltage as a function of phase difference between the two input signals that are maintained in phase lock.

(b) Loop filter. Tuning filters integrate and scale phase/voltage input to produce noise reduction at its output. Slower narrow bandwidth loop filters supply greater noise reduction at the expense of signal dynamic range.

(c) Voltage Controlled Oscillator (VCO). Quartz oscillator crystals control VCO frequency response as a function of input voltage. Loop filter inputs are used to adjust VCO frequency to effect PLL tracking feedback.

(d) Frequency dividers. A variable phase matching range is maintained in the PLL feedback path by programmable counter and divider ratio logic that steps output frequency in controlled increments of the input reference frequency.

f. Phase tracking. Phase tracking is controlled by the operation of PLL circuits. Time-varying carrier signal inputs create a voltage response in the phase detector due to a phase difference between the input and reference signals. Carrier loop filters amplify and clean this phase/voltage response to generate a feedback frequency (phase) shift in VCO output. Range matching is then supplied by frequency dividers to prepare the updated reference signal for feedback to the phase detector, which closes the PLL circuit. These tracking system controls are performed by microprocessor chips, and used to monitor incoming GPS carrier signals. Accumulated phase travel is recorded at user-defined GPS time epochs. These cycle count values are stored in binary form in receiver memory.

(7) Internal data memory. Data storage is handled by magnetic media that is typically installed in blocks of 1-10 MB per memory board. The manufacturer upgrades memory at additional cost to the user. Microprocessors control read-write functions through a LCD screen and user interface, or by pre-programmed survey controls.

g. User survey controls. Most COTS GPS systems are equipped to allow a range of user programming options that specify its operation on a given survey. Some systems have limited user input capabilities (eg., power on/off) to simplify installation and use at permanent sites, such as on construction equipment. These types of systems are designed to give continuous, real-time position outputs to external radio-link, processor, or software systems. Other GPS units consist of stripped down OEM board processors used for highly specific positioning and navigation applications controlled by a custom computer system.

(1) Observing parameters. These options must be set to specific values before data logging commences.

(a) Mask angle. Mask angle defines the cutoff elevation angle (0-90 degrees) above the horizontal plane used for search, acquisition, and tracking of GPS satellites.

(b) PDOP cutoff. Position Dilution of Precision (PDOP) describes expected GPS code position quality. PDOP cutoff defines the value below which the receiver will cease tracking a GPS satellite signal.

(c) Data logging rate. Specifies the time increment that will initiate recording a new block of GPS observations to memory for storage and downloading.

(d) File name. Alphanumeric code that identifies individual session files in receiver memory. Typically COTS GPS receivers will supply a default file name that can be changed during downloading or post-processing.

(e) Antenna height. The user can enter antenna height measurements into the session file, or a default value of zero is typically provided.

(2) System parameters. Because GPS receivers are designed for many different surveying applications, alternate operational modes may be available to the user, which must be selected in advance.

(a) Data type. This is a generic setting that designates whether the receiver will automatically reduce the scope of observations that will be logged to memory.

(b) L1/L2 operation. P-code tracking in crypto-keyed receivers must be disabled before normal data logging will be allowed. Full wavelength L2 carrier phase measurements are unavailable due to anti-spoofing (A/S), therefore, cross-correlation with L1 phase or signal squaring is used to reconstruct L2 phase for dual frequency applications.

(c) Communications. Typically any functions related to external communications need to be disabled for proper static surveying operations.

(3) Operating parameters. Most receivers have customized features that provide convenient status information to the user.

(a) Power controls. Systems with multiple power source inputs will have some means to check the level of battery charge or a switch to enable a particular power port.

(b) Tracking status. Various screens are available to determine the number of activated SV tracking channels, L1/L2 signal acquisition and lock, and code position updates.

8-10. GPS Receiving System Performance

a. General. The RMS error of GPS receiver PLL carrier phase tracking can be characterized by the phase measurement precision, and by systematic errors that distort the clean GPS signal waveform during its transmission, propagation, and reception. Thermal noise and oscillator deviations are principle sources of random noise in GPS receiver units. Systematic error is mainly caused by physical correlation between the GPS signal and its path environment. The adequacy of GPS surveying can be established in part by these internal and external receiving system errors. GPS receiving system performance is a major factor in determining whether surveying systems requirements have been met. Following is a description of performance and operational limitations that must be accounted for in the design and execution of GPS monitoring surveys.

b. Receiving system noise. Superior phase tracking performance is obtained if the formal (random) error in the phase measurement, and in the VCO clock stability, are limited to a sequence of low noise, zero-mean error states. Under healthy observing conditions, the random error in carrier phase tracking can be modeled directly from the values for received signal carrier-to-noise power density ratio (c/n_o), and PLL filter noise bandwidth (B). These parameters determine an effective tracking channel noise figure in each receiver. Major random error sources in GPS signal tracking are: receiver system thermal (Gaussian) noise (which is dependent on received signal frequency), and short-term phase tracking jitter induced by random deviations in PLL stability and feedback control inputs associated with receiver clock performance (Allan variance of local oscillator). For most GPS static surveying applications, a base resolution of 1/100 part of the wavelength is used as a practical limit for best-case tracking performance. By combining minimum detectable carrier-to-noise (C/N) deviations with a lower-end PLL noise bandwidth (2 MHz typical), at nominal L1/L2 wavelengths, and accounting for clock stability performance in modern receivers, a maximum of 2-3 mm of phase uncertainty is expected for GPS phase measurements.

(1) Thermal noise. The equation for approximating the error on the carrier phase (L1 or L2) due to thermal noise is:

$$\sigma_{PLL} = (\lambda / 2\pi)(\mathrm{sqrt}[B / (c/n_0)])\ \ (m) \tag{Eq 8-1}$$

where

B is the carrier tracking loop bandwidth (Hz),
λ is the wavelength of the carrier (m),
c/n_0 is the carrier-to-noise density expressed as a ratio,

and

$c/n_0 = 10^{(C/No)/10}$ for C/N_0 expressed in dB-Hz.

This equation gives a nominal value for the L1 noise of 0.2 mm for a 2 Hz noise bandwidth and a C/N_0 value of 45 dB-Hz. There is an inherent tradeoff between phase measurement resolution and dynamic tracking range in the general design of PLL filters. Better performance on monitoring projects will be obtained from narrow bandwidth correlators. This is because the ground antenna is stationary for the duration of the observing session and satellite-receiver dynamics are always well below PLL tracking thresholds. Higher phase resolution at lower PLL bandwidth is practically limited by received noise power and tolerance to sluggish loop response times.

(2) Clock stability. The equation for approximating RMS phase jitter in the tracking loop has been given by,

$$\sigma_2 = (\lambda / 2\pi)\ P\ (\sigma_A)\ f_L / B \cdot (m) \tag{Eq 8-2}$$

where

P is an empirical constant based on the PLL loop-order,
f_L is the frequency of the carrier (Hz),
σ_A is the Allan deviation expressed as a function of short-term gate time (τ),

Allan deviation is determined for a given PLL filter according to the expected receiver clock frequency stability ($\Delta f/f$) as a function of the loop filter bandwidth.

$$\sigma_A = (\lambda / 2\pi)^{-1}\ (\sigma_\theta)\ /\ (\omega_L\ \tau) \tag{Eq 8-3}$$

where

$\tau = B^{-1}$ (sec),
$\omega_L = 2\pi f_L$ (rad/sec).

This equation gives a nominal value for the L1 noise of 0.7 mm for an 18 Hz noise bandwidth and specified Allan deviation (σ_A) of less than $1 \cdot 10^{-10}$ (dimensionless). The performance of the Voltage Controlled Oscillator (VCO) also contributes to the phase measurement resolution through the random clock drift tolerance term (Allan variance) that impacts the synchronized reference time epoch value reported by the VCO. Actual phase measurements consist of a time-smoothed PLL output that is dependent on the clock stability and PLL correlator bandwidth.

(3) Received signal noise. Signals arriving from GPS satellites are received as continuous, quasi-periodic waves, composed of code and data modulated carrier signals plus Doppler frequency shift. Antenna excitation and response is caused by local electric field variations at the antenna phase center. Pure carrier signals (e.g., sine waves) have a line spectrum of discrete frequencies (harmonics), described mathematically by Fourier series analysis of the antenna-input data. The near-field electric field at the antenna also contains signal distortion effects and noise from: local sources of RF interference; coupled EM interactions (imaging) between the antenna/ground plane, local electric field, and nearby conductors; diffraction signal scattering at the edges of the ground plane; signal reception through side lobes (antenna illumination below ground plane); and signal multipath. The presence of external EM noise and environmental field effects lowers the spectral purity of transmitted GPS L1/L2 signals. Unwanted noise power components are characterized as random signals, described statistically by signal power spectral density, and noise field strength parameters of the antenna. L2 signals are generally noisier than L1 signals, and this noise generally reduces the precision of carrier phase measurements. Measurement noise is also modeled as random error produced by physical correlation in the generation, propagation, and reception of GPS signals.

c. Correlation in GPS data. Correlation describes the extent to which measurement errors will be similar as a result of common external observing conditions and as a result of math modeling applied to the data. High data correlation reduces the statistical independence between measurement errors and lowers the significance of random error parameters (mean and variance). This highlights the importance of using error treatments in post processing that do not neglect data correlation. Both spatial and time correlation can influence GPS performance and if possible their effects on error estimates should be accounted.

(1) Physical correlation in GPS data. GPS signal behavior is understood to be highly correlated when common-mode conditions occur due to geometry, environment, and system specifications used to mechanize GPS operations. Important sources of physical correlation in GPS data are: geometry of the satellite constellation; ephemeris (orbit) errors; frequency dependent atmospheric propagation delays; satellite and receiver clock synchronization; receiver system throughput latency; spectral receiving system noise; and multipath interference. Spatial correlation in GPS data can be largely related to baseline length and common mode GPS system status. Biases are minimized by differencing data and by allowing satellites-in-view to change position (over time) which yields a range of Dilution of Precision (DOP) states throughout the survey. Changing satellite geometry tends to randomize small residual biases that occur over short baselines. Correlation times in GPS data are based on both the session length and the data sample rate needed to span a large percentage of independent (uncorrelated) observations. If the session is averaged for longer than the total period of the correlated error signal, then short-term measurement deviations will be evenly distributed about an unbiased mean value. Data sample rates lower than the data correlation time produce unrealistically low errors.

(2) Mathematical correlation in GPS data. Double difference combinations made during baseline processing will create mathematical correlation in the processed output--especially as a tendency to magnify initial measurement errors according to statistical error propagation laws ending up in the covariance matrix of parameters. As a result, error estimates (baseline component standard deviations) are generally overly optimistic. Other sources of math correlation are determined by the specific processing scheme implemented in the GPS software. The most common sources are due to: data differencing (single, double, triple); least squares filtering; dual frequency L1/L2 atmospheric delay correction; L1/L2 cross-correlation used to recover L2-carrier data under A/S; dual frequency ambiguity

resolution techniques (widelane, narrowlane); choice of reference satellite; specific SV double difference combinations; and the elimination of nuisance parameters in the normal equations matrix. The manner in which math correlation is handled is largely dependent on level of rigor used for statistical error treatment in the software and the proper formulation of error estimates in the covariance matrix of parameters.

d. External data correlation. Studies of the effects of physical correlation on accuracy estimates in GPS relative positioning have shown that double difference residuals are subjected to empirical modeling based on various forms of the autocovariance function. The study method was designed to isolate a distinct error estimate for both mathematical and physical correlation in GPS double difference residuals. Significant trends in the residuals were modeled to describe baseline error as a consequence of neglecting physical data correlation. Results over medium length baselines indicate that standard deviations of coordinate components are typically reported at much lower than actual values (perhaps by a factor of two). Other relevant findings include a determination of error correlation times for L1 and L2 GPS double differences persisting over 4-5 minutes of data. This could be interpreted as the minimum observing time period needed to produce independent measurement error values where physical correlation is not explicitly accounted for in the processor's weighting scheme. A corresponding 20 percent increase in the standard deviation of each coordinate component is indicated. Other empirical results deal with fixed and float ambiguity variance ratio estimates that are compared against the convergence times between math and physical correlation trials. Convergence to typical error levels reported by the software (variance ratio of 7.0) required about 10 minutes to occur. Finally, GPS double difference observations can be positively correlated for a period of up to 20 minutes on shorter test baselines. These results are an important indicator of expected performance on monitoring networks for two reasons. First, baselines are expected to be shorter than used in the above trials (1-2 km), therefore the reported impacts of correlation could be used as an upper limit for tolerance to physical correlation in deformation studies. Second, guidance presented in Section I is mainly compatible with these independently established GPS observing tolerance limits.

8-11. Sources of Error in GPS Measurements

a. General. The observation equation for the GPS carrier phase can be written in length units as:

$$\Phi = \rho + c\,(dT - dt) + \lambda N - d_{ion} + d_{trop} + d_{mp} + \text{noise} \quad \text{(Eq 8-4)}$$

where ρ represents the geometric range between the satellite and receiver, c represents the speed of light in a vacuum, dT and dt represent the receiver and satellite clock errors respectively, λ represents the signal wavelength, N the integer cycle ambiguity, d_{ion} represents the phase advance due to the ionosphere, d_{trop} represents the delay due to the neutral atmosphere (predominantly the troposphere), d_{mp} represents the delay due to multipath in the antenna environment, and noise in the signal. Additional small terms such as satellite and receiver hardware delays have been ignored. By differencing observations recorded simultaneously at two receivers from two satellites, any common mode errors at either the satellites or the receivers should cancel. The error terms left in the double difference observable are d_{ion}, d_{trop}, and d_{mp}--as the effect of receiver error, satellite clock error, and satellite position error are almost completely removed. A differential ambiguity term (DN) is retained in the double difference equation. The noise component has been amplified in the double difference, by assuming that noise is equal for the raw observations at two receivers, and the noise of the double difference observation is then approximately twice as large. This increase is the trade-off accepted for greatly reducing the impact of the clock errors. Over very short baselines with negligible height difference the trade-off is even more worthwhile, since atmospheric effects almost completely cancel.

b. Cycle slips. Correctly fixing ambiguities requires continuous carrier phase observations with no cycle discontinuities over the observation time series. Any cycle slips must be removed prior to estimating the station coordinates. The data sets from each occupied station are pre-processed individually to scan the carrier phase observation time series for large jumps and excessively noisy data. An output file of the pseudorange and carrier phases is produced that is free of large cycle slips. Cycle slips of a small magnitude (at the level of several tens of cycles) are best detected from the time series of double difference observations, where many of the potential biases have canceled. Cycle-slip detection is generally implemented as an automated data cleaning process that depends on high quality data and sufficient redundancy to allow lots of data to be rejected (sometimes unnecessarily).

c. Baseline length. A simple expression for relating common mode GPS range error (Δ r) to baseline error (Δ b) uses the ratio of baseline length (b) to satellite range (R).

$$(\Delta b / b) = (\Delta r / R) \qquad \text{(Eq 8-5)}$$

For satellite range of 20,000 km and baseline length of 1 km, a common mode error of 20 meters is necessary to produce 1 millimeter of baseline error. This relationship emphasizes the advantage to maintaining short baselines on high precision networks. Short baselines should limit common GPS errors to less than 20 meters and permit cancellation of highly correlated errors.

d. Atmospheric delay. Ionosphere and troposphere delays are expected to be highly correlated over short baselines, although small residual effects may persist depending on atmospheric differences between receiver stations. For this error to increase to harmful levels would require baselines over 1 kilometer, or very substantial station height differences (which may occur on some dam sites). Uncorrelated delay bias is modeled and removed from the data on medium range baselines (10-100 km). However, these correction schemes are not accurate enough to determine slight differential biases at short baseline noise levels.

e. L1/L2 data combinations. GPS software will allow the user to process data in combinations of L1 and L2 carrier frequencies each having different levels of observation noise. Any combination of these two observables (e.g., ionosphere-free L1/L2) will increase noise levels due to error propagation. Over short baselines the ionospheric effect is expected to cancel so there is no advantage to be gained by using anything other than the L1 observations for positioning purposes. L2 observations however, could be useful for cycle slip detection and data quality control. The L2 residuals are approximately 1.5 times noisier (RMS 6.6 mm) than the L1 residuals (RMS 4.4 mm), and the L3 residuals are approximately 3 times noisier (RMS 12.8 mm). Figure 8-1 shows how some of the structure in the L1 residuals is magnified by the L3 combination. The symmetric pattern of the residuals is due to the particular formulation of the double difference observations.

f. Satellite geometry. The spatial distribution of satellites in the sky will influence how random error propagates into the final position. Since GPS satellites are not uniformly distributed, certain areas of the sky will have less satellite coverage at a given time. If GPS satellites are evenly and widely spread out, then stronger geometric intersections are possible for code range positioning and carrier phase measurements. Because there is total lack of sky coverage below the GPS antenna, vertical DOP values and GPS height errors can be 1-2 times greater, respectively, than HDOP and horizontal position errors.

g. Blunders. Operator mistakes produce large discrepancies in processed GPS data. Only system redundancy built into the observing scheme can detect blunders--see Section IV. Two common survey blunders are incorrect antenna height measurements and incorrect filenames entered into the receiver.

h. Multipath. See Section IV of this chapter.

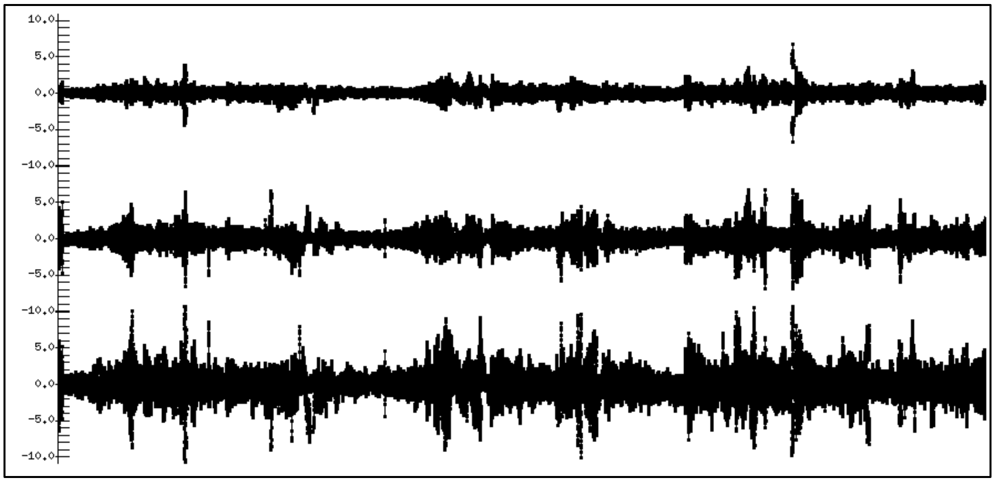

Figure 8-1. Typical carrier phase residual noise levels from double difference processing; from top to bottom, (a) GPS L1 frequency, (b) GPS L2 frequency, (c) GPS L1/L2 widelane combination.

8-12. GPS Performance on Monitoring Networks

a. General. Results of accuracy performance and operational adequacy of GPS surveying for monitoring applications are presented in this section. Data collected under controlled conditions and at USACE monitoring projects are described. Simulated deformations are used to test GPS capability to detect movement over short baselines. Comparisons are made against conventional surveying performance and requirements outlined in Section I of this chapter.

b. GPS performance trials. Factors used to evaluate GPS performance include: user-set parameter values for data collection and processing; observing session length; satellite constellation status--to determine expected repeatability, accuracy, and/or problems with GPS use on monitoring projects. Results are empirically based on field tests and GPS data analysis.

(1) Coordinate repeatability. Figure 8-2 shows coordinate repeatability obtained from 42 GPS data sets collected in short-session time blocks (15 minutes, 20 degree mask angle) with fixed values for integer ambiguities. Discrepancies in the height component vary the most, with the largest variations being correlated to epochs with low numbers of observations. Two-sigma (95%) repeatability is approximately 6 mm for the height component and a peak height discrepancy of almost 10 mm. Horizontal coordinate components have generally better repeatability than vertical components. The level of repeatability and bias are due to systematic error effects not averaged out over the short time spans and likely caused by multipath. Baseline component formal errors with the height residuals, determined from the trace of the inverted normal equation matrix are representative of the Dilution of Precision (DOP) for the satellite constellation over the solution epochs. Periods of high height residuals correspond to times where no satellites are below approximately 30 degrees. Therefore, for short observation periods, some pre-observing planning can minimize the potential DOP values.

(2) Solution convergence. Solution convergence to millimeter level accuracy defines the session length requirement for establishing project fixed control in surveys conducted on reference networks. Reference stations normally would be occupied for many hours during production surveys. Figure 8-3 shows convergence times for simulated reference network baselines. Convergence to the millimeter level

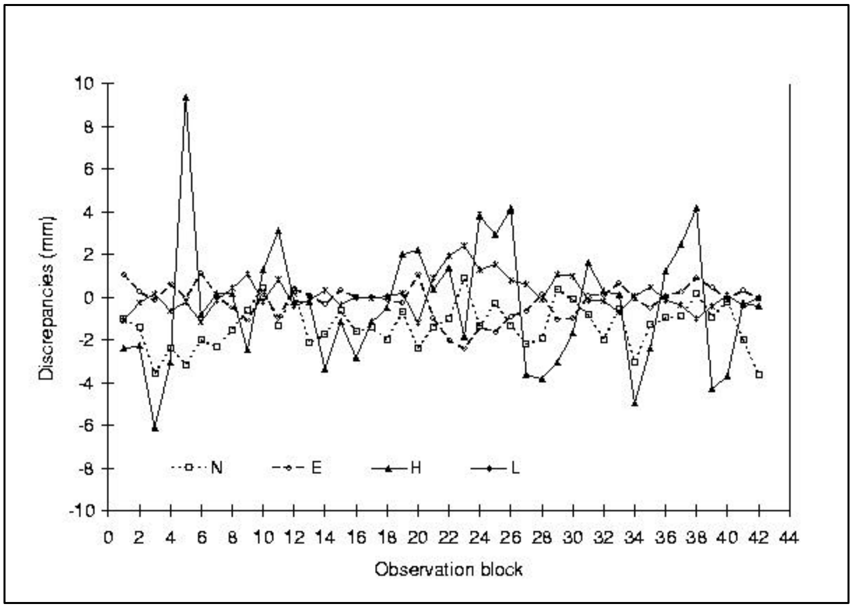

Figure 8-2. GPS coordinate component repeatability from 15-minute sessions over short baselines.

takes place within several (3-5) hours in low multipath environments. Horizontal coordinate components converge very quickly (less than one hour) leaving the height component more variable. In higher multipath environments, convergence takes place almost one order of magnitude later, which is within ten or twelve hours. Not only does the convergence take longer, but there is a greater variation of the position components over the whole position time series. These results are particularly important for selecting the location of reference stations where high accuracy control is required and that the role of multipath is crucial when attempting to use GPS for positioning tolerances at the millimeter level.

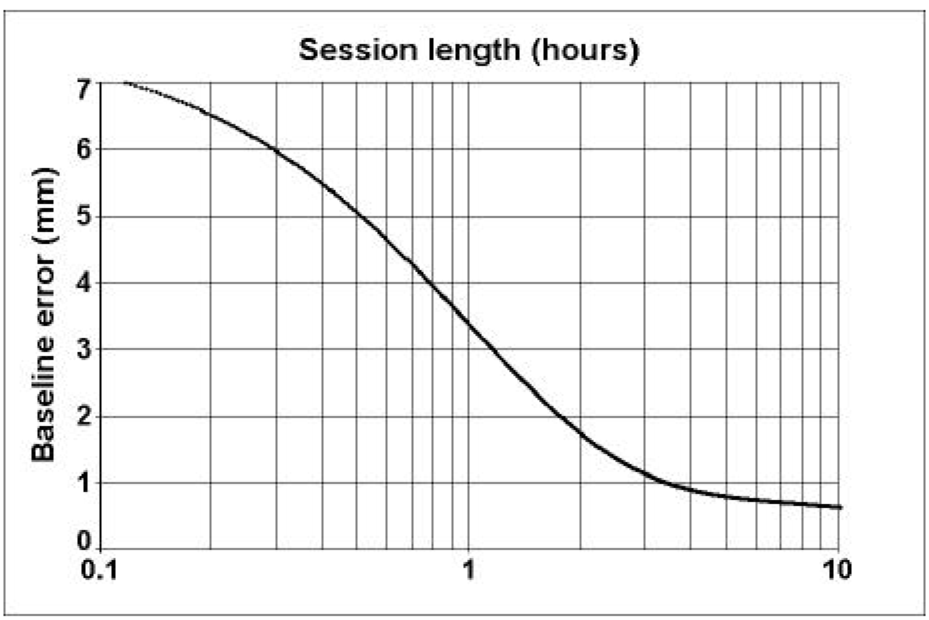

Figure 8-3. Accuracy convergence time plotted as log session length needed to exceed average baseline position error.

(3) Multipath errors. Signal interference from multipath is described in Section IV. The plots presented below illustrate some of the signs of multipath in GPS carrier phase data. Figure 8-4 shows an example of high levels of multipath on one satellite pair. The time difference between various peaks on the plot are approximately 230 and 240 seconds with a peak value of approximately 4 cm, which is almost 80% of the total limit for L1 multipath before cycle slips are expected to occur. Figure 8-5 shows three traces from two satellite pairs to see the reduction in multipath as the mask angle increases. These plots show that considerable multipath can still remain when the mask angle is set up to 20 degrees.

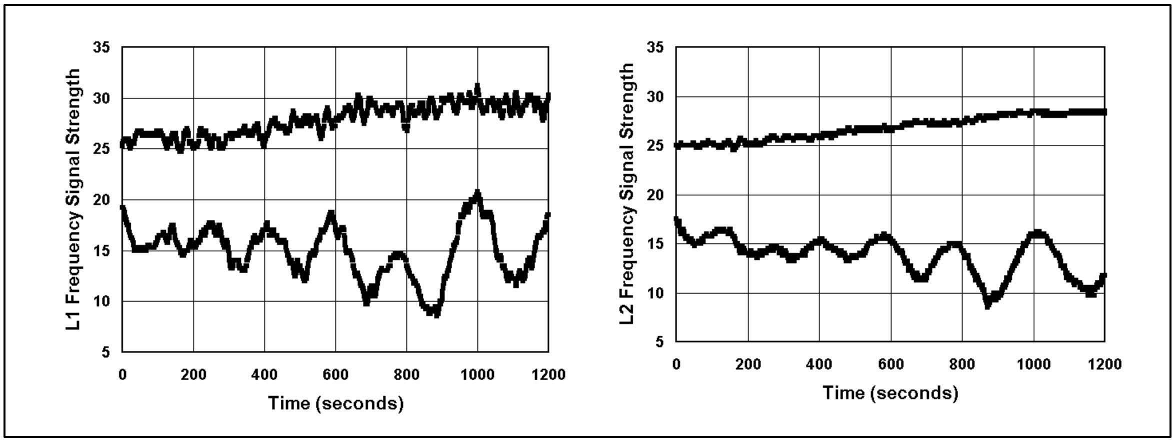

Figure 8-4. Typical GPS multipath curves found in L1 (left), and L2 (right) signal strength profiles. Lower series represents high multipath error, upper series represents normal signal strength profile.

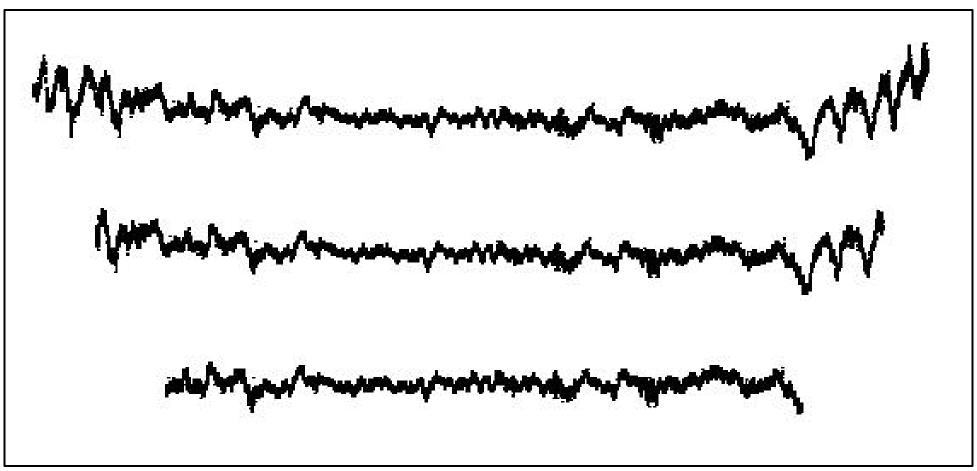

Figure 8-5. Multipath error profile plotted against processing mask angle; satellite elevation top to bottom, (a) 10 degrees, RMS 6.3 mm (b) 20 degrees, RMS 4.4 mm (c) 30 degrees, RMS 2.9 mm.

(4) Ambiguity resolution. When integer ambiguities were fixed for 42 blocks of 15-minute data, three blocks had at least one satellite incorrectly fixed, which equates to 7% of incorrect blocks, but only 3% of incorrect ambiguities over all 42 blocks. Re-processing with different mask angles did not improve the results and in fact produced more incorrect ambiguities in more sessions. These results can be considered typical for GPS monitoring applications. Constraining the a-priori station coordinates to one centimeter so that all of the ambiguities in all the blocks are correctly resolved makes an improvement.

(5) Satellite ephemeris. Evaluation of monitoring data sets indicates that for static mode sessions either the broadcast or precise ephemeris can be used without causing significant changes in the solutions.

(6) Antenna mask angle. Changing the satellite elevation mask angle will produce slightly different processed coordinates. Discrepancies between solutions for 20 and 30 degree mask angle are generally less than 1 mm except for the height components thus producing a large difference in the coordinates. High mask angles (>20-30 deg) tend to eliminate too much raw data, depending on the number of satellites-in-view. Using lower elevation satellite data will improve the overall satellite geometry but the data is usually of poor quality. As is the convention with lower order GPS surveys, a 15-20 degree mask angle is recommended, especially where additional height control is available on-site. In practice, data quality indicators can be used to find an optimal mask angle for baseline processing.

(7) Session length. Height coordinates deviations over small networks are at the sub-centimeter level--sometimes even at stations with high multipath. As long as the integer ambiguities can be reliably resolved, then short observation sessions of fifteen (15) minutes should be able to achieve results within 6 mm 95 percent of the time. Simulated displacement tests show convergence to less than 1 mm in the coordinate components after approximately 15 minutes with one-second data.

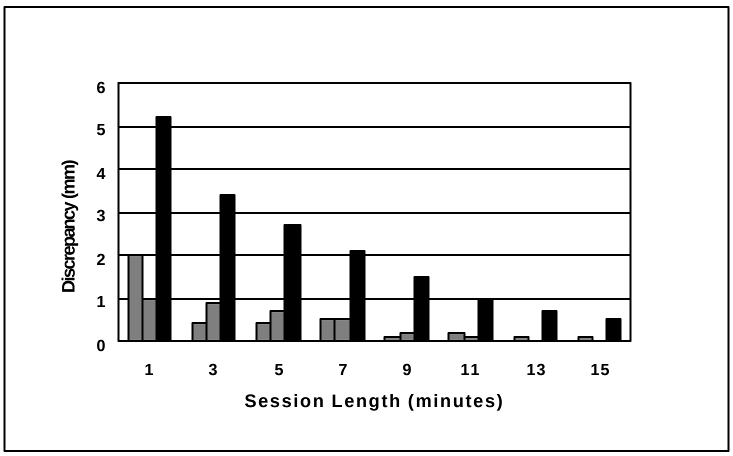

Figure 8-6. Convergence of coordinate component discrepancies to the true position with a simulated displacement of 2.5 mm. For each session the components are plotted north, east, height respectively.

Small displacements (millimeters) can be detected using two reference stations, having highly accurate relative positions determined from long observation sessions, and high quality carrier phase data (low systematic error). Figure 8-6 shows convergence in northing, easting, and height components every two minutes over a 15 minute session representing optimal performance for GPS deformation surveys in open areas. Slightly longer sessions (20-30 minutes) provide additional data redundancy and lower multipath effects. Very short baselines (10 m) measured directly across the upstream and downstream edges of a dam crest have compared to about 1 mm with precise leveling data.

c. GPS monitoring trials. GPS surveys can accurately reproduce positioning with conventional instruments with 2-3 mm point positioning error at 95 percent confidence level. Figure 8-7 shows a typical comparison between GPS and conventional surveys with average discrepancy of 1-3 mm and up to 5 mm can occur under slightly adverse conditions. Typical baseline component standard deviations are optimistically reported at less than 1 mm, data adjustment variance factors range from 1.2 to 4.3 (based on software) also optimistic due to a one second data logging rate. Error estimates in the covariance matrix of parameters are scaled up by the variance factor value to produce realistic error reporting. Horizontal point confidence ellipse dimensions range from 0.1 to 0.5 mm, also optimistic by perhaps a factor of ten based on repeated surveys on monitoring networks. Baseline solutions should have fixed integer ambiguities, float solution are generally unacceptable. A-posteriori variance ratios (RMS) between fixed and float solutions are found to range between 10 to 30, with an average of 20, indicating reasonably high confidence in the fixed integer solution. A minimum value of seven (7) should be produced or problems with ambiguity resolution might be suspected. Sometimes GPS data is unusable or will not process due to poor observing conditions

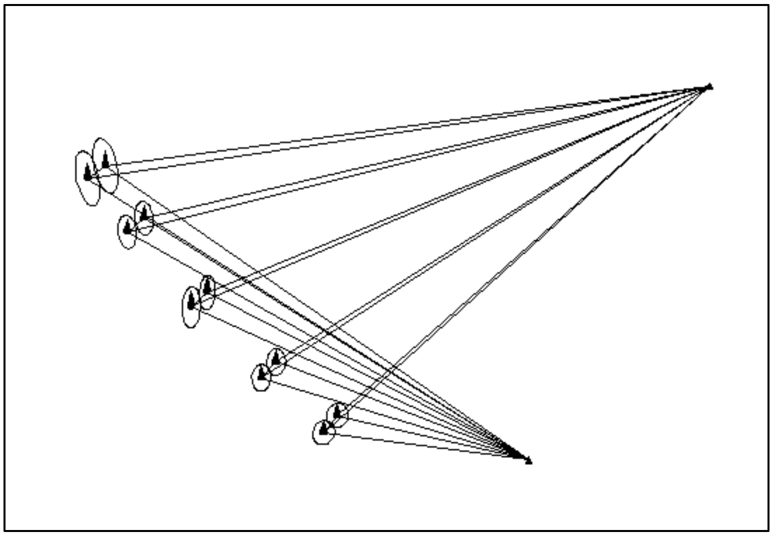

Figure 8-7. Network map of 10 monitoring points compared between GPS and precise conventional surveying results. Error ellipses are plotted at ten times actual size. Overall differences are less than 2-3 mm in all cases.

Section III
Data Quality Assessment for Precise GPS Surveying

8-13. Quality Assessment Tools

a. General. A major task for meeting accuracy requirements on GPS deformation monitoring surveys is to obtain high quality raw data and to eliminate or minimize low quality data whenever possible. Data quality indicators are used to assess the effectiveness of a given GPS session. The following paragraphs describe techniques to evaluate GPS monitoring data sets for quality control (QC).

b. Mission planning software. See Section I of this chapter.

c. RINEX data processing. Pre-processing begins with converting binary GPS data into a Receiver Independent Exchange Format (RINEX) file. Most commercial GPS post-processing software packages include a computer utility for converting to RINEX and for importing translated RINEX data files to the main baseline processor. Software applications are available over the Internet for GPS data QC using these RINEX files. QC programs are designed to extract observing status and summary information about a GPS session and are more specialized than simple RINEX converters.

(1) RINEX format. RINEX files contain raw GPS data in a readable ASCII text format that allows the user to directly inspect and edit the survey session. RINEX observation files contain station metadata in a header file followed by a time sequence of GPS observation blocks. RINEX ephemeris files contain GPS orbit parameters that define the position each satellite as a function of time. Further details on the structure and content of RINEX formatted data files can be obtained from Internet resources (e.g., IGS website). A short description of RINEX observation file information is presented below.

(2) RINEX header. The header section appears first in a RINEX file. The header contains the following information: RINEX Software Version; Conversion Date; Station Marker Name; Observer/Agency; Receiver/Antenna serial number(s) and GPS antenna type (special code for each type); Approximate (user) Position (WGS84 X-Y-Z); Antenna Height Offsets (delta H/E/N); Data Types (actual logged set of observables); Time of First Observation (in GPS Time); Text Comments (user entered); and an End of Header record. Some header fields may be empty because the file is populated initially with information that a user enters in the receiver. The header file can be edited to add information about the project by using the comment line header code.

(3) RINEX time tags. RINEX data blocks start with a GPS time tag which includes: Year, Month, Day, Hour, Minute, Second in GPS time, along with the actual number of satellites represented in each data block, followed by each unique satellite identifier number. Every logging epoch that contains data will have an initial time tag. If data was not logged, then the corresponding time epochs will be skipped until new data is acquired.

(4) RINEX data. Observation blocks are organized into seven (7) columns containing: L1 phase; L2 phase; L1 C/A code; L1 P(Y) code; L2 P(Y) code; L1 SNR; and L2 SNR (signal-to-noise ratio) data types, in that order. Phase is recorded in cycles, code is recorded in meters, and SNR is either recorded as a manufacturer supplied gain equivalent (similar to dB), or as a conventionally scaled SNR value ranging between 0-9. Individual observation blocks are recorded sequentially for each logging epoch until the end of the session (file) is reached. Some data blocks may contain missing data records for one or more data types. These will be listed as blank or zero entries in their respective column(s).

d. TEQC data processing. One widely used QC application is called TEQC (translation, editing, and quality control) which is distributed on the Internet by UNAVCO (University NAVSTAR Consortium).

(1) TEQC software. TEQC offers a command line DOS or UNIX system interface and is used for general data pre-processing. Users must download the compressed TEQC application software and a companion user manual to operate the software. The program defines a GPS session as a single-site GPS receiver setup where full GPS data has been logged. TEQC requires a RINEX format GPS data file and a RINEX format GPS ephemeris file for running full quality control functions. RINEX ephemeris files can be downloaded from the Central Bureau of IGS (International GPS Service for Geodynamics) public FTP site. Ephemeris files are compiled from data collected at IGS data centers. Each IGS station contributes to the global adjusted precise GPS ephemeris file for each day. Once these files have been pre-processed, basic graphics programs ('qcview.exe' and graphics driver 'egavga.bgi') are available for plotting TEQC results (also available on-line from UNAVCO).

(2) TEQC descriptive statistics. Data pre-processing packages like TEQC provide the following output to aid in the evaluation of a GPS session.

(a) Status information. A summary file is created that contains information on continuous L1/L2 tracking status for each SV; input data and ephemeris filenames; session start and stop times; data logging interval; total number and list of satellites observed; receiver tracking capability; at different elevation angles the number of observations, possible observations, and missing observations; clock drift and rate; clock resets and gaps; number and percentage of cycle slips; time of first and last observations; session length; and other status statistics. The summary file also contains parameters used by the QC program.

(b) Observation summary. For each SV, total number of observations of each type (i.e., L1, L2, C/A, etc.), above horizon, above mask angle, and for each observable; L1/L2 code multipath levels and cycle slips for each SV; SV elevation angles and signal strength counts summarized in 5 degree bins.

(c) Auxiliary files. In addition to the summary file contents listed above, for each session, each satellite, and over each recording epoch, auxiliary files are created that contain SV elevation angles, azimuths, L1/L2 signal strength data, and L1/L2 code multipath indicators. These can be readily plotted and examined for each session.

8-14. GPS Session Status

a. General. Data quality is highly related to the observing status during a given GPS session. Actual GPS survey results are compared with expected performance to detect poor quality data. Data editing and removal is one means to improve the GPS session. Guidance presented below is meant to highlight problem areas with GPS data and to list them as a group for convenient reference.

b. Satellite health status and NANU warnings. Satellites designated with an unhealthy status, or those undergoing prescribed orbit maintenance maneuvers, will alert the receiver to its degraded situation and automatically store this condition flag in the raw data. Users need to become aware of any scheduled changes in constellation status by checking NANU bulletins. The following NANU message types are used.

(1) Forecast outages. Forecasted NANU messages begin with the prefix "FCST": FCSTDV Forecast Delta-V gives scheduled outage times for Delta-V maneuvers. The satellite is moved for maintenance and the user may be required to download a new almanac. FCSTMX Forecast Maintenance gives scheduled outage times for Ion Pump Operations or software tests. FCSTEXTD Forecast Extension

extends the scheduled outage time "Until Further Notice"; references the original NANU. FCSTSUMM Forecast Summary gives the exact outage times for the scheduled outage, including the FCSTEXTD; sent after the maintenance is complete and the satellite is set healthy to users; references original NANU. FCSTCANC Forecast Cancellation cancels a scheduled outage; new maintenance time not yet determined; references the original NANU. FCSTRESCD Forecast Rescheduled reschedules a scheduled outage; references the original NANU.

(2) Unscheduled outages. Unscheduled outage NANU messages begin with the prefix "UN": "UNUSUFN Unusable Until Further Notice" notifies the user that a satellite will be unusable to all users until further notice. UNUSABLE with a reference NANU closes out an UNUSUFN NANU and gives the exact outage times for the outage; references the UNUSUFN NANU. UNUNOREF UNUSABLE with no reference NANU gives times for outages that were resolved before a UNUSUFN NANU could be sent.

(3) Other. Other outage NANU messages can cover any remaining conditions. USABINIT Initially Usable notifies the user that a satellite is set healthy for the first time. LEAPSEC Leap Second is used to notify users of an impending Leap Second. GENERAL informs the user of general GPS information.

c. Continuous L1/L2 signal lock. Maintaining continuous phase lock on both L1 and L2 signals is a critical requirement for obtaining high quality data. Loss-of-lock on any satellite indicates a problem with its signal reception and tracking. Intermittent data gaps should be suspected of having lower quality data at or near the affected signal loss times. GPS L2 signals will generally experience tracking problems before L1 signals (on same SV) due to greater relative noise power on L2. If possible, only data collected from satellites that maintain continuous signal lock should be used for final baseline processing.

d. SV tracking time. Signal tracking is related to the amount of time a given GPS satellite is in continuous view of the receiver/antenna. Satellites that are just rising, setting, or are only in view for short periods of time (less than 15 minutes) are to be suspected as unfit. Problems encountered with data collected in a short tracking window includes high data correlations based on short averaging time and low signal strength. Mission planning can be used to rank each satellite by tracking window length for an overall comparison between SVs throughout the session (Figure 8-8).

e. Satellites-in-view. GPS satellites are more densely placed over the mid-to-lower earth latitudes. Southern sky exposures in CONUS yield higher satellite-to-receiver coverages. A minimum of five (5) satellites is recommended for reliable GPS processing results. Generally, eight (8) or more GPS satellites are available at optimal observing times. Extra satellites in view increases data redundancy and provides the user the option to select only the highest quality data within a session. A percentage of GPS data can be judiciously removed prior to re-processing. A comparison is made of before and after processing statistics to judge its impact on solution quality. Line-of-site coverage can be determined before fieldwork begins using GPS mission planning software. Sky view plots (Figure 8-8) are modified to fit a particular site by horizon templates that graphically trace any shadow zones on the sky visibility diagram (e.g., polar-plot with an above view perspective). Areas with a denied signal are defined by a series of approximate cutoff elevations and azimuths. These are gathered with compass and inclinometer instruments during reconnaissance surveys. Obstructions are areas with moderate to high topographic relief (hillside, slopes, embankments), large solid objects (buildings, walls), or permanent objects that may block antenna signal reception (trees, poles, overhead wires). Satellite elevation and azimuth data can be extracted as numerical values from RINEX files using TEQC software, or viewed as skyplots generated from mission planning software.

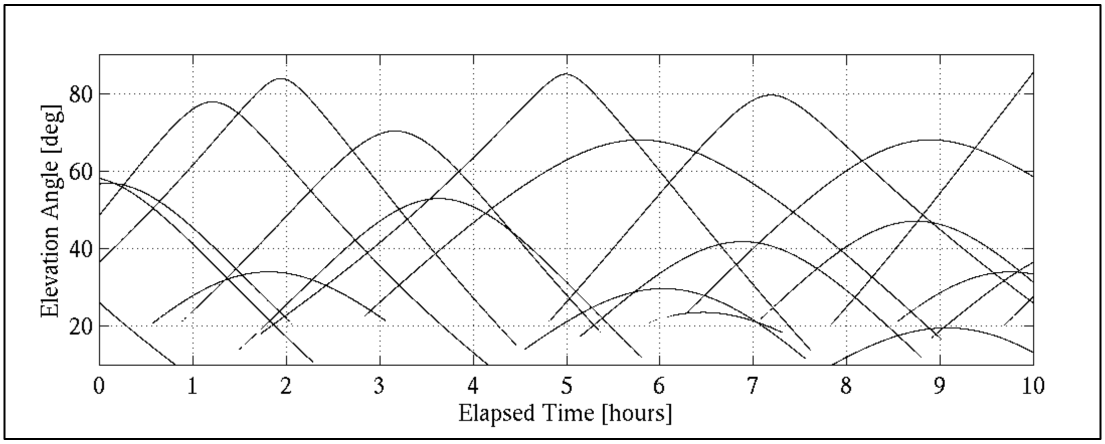

Figure 8-8. Skyplot of available GPS satellites plotted as a function of elevation angle and elapsed time (azimuth).

f. Dilution of Precision (DOP). GDOP and PDOP (Geometric and Position DOP respectively) are measures of geometric and position strength related to satellite constellation geometry and user range error. PDOP is computed as the ratio range error to the single station position error used in code range positioning. PDOP has a minimum theoretical value of one (1), which represents the ideal case of no position error increases occurring due to satellite geometry. Periods of PDOP greater than four (4) are suspect in practice. Both the geometry and the number of tracked SVs are highly correlated to DOP values. Effects of low and high DOP windows can be observed in GPS performance results.

g. Satellite elevation angle. Satellites at low elevations generally produce low quality signals because of signal multipath, refraction, attenuation, and reduced antenna gain. In theory, data from lower elevation satellites will improve satellite geometry, however, any benefit from geometry is offset by poor signal quality. Satellites at elevation angles below 20 degrees above the local horizon, and directly at zenith, experience the greatest problems with signal quality.

h. L1/L2 signal strength. Signal strength on L1/L2 carriers is measured by the receiver as a carrier-to-noise density (C/N) ratio. C/N is a function of transmitter power; satellite elevation angle; antenna gain pattern; signal attenuation; and receiver noise power. GPS signal quality is related to the behavior of its signal strength profile. Low signal strength values indicate relatively higher noise power, and therefore greater uncertainty in phase measurement. Erratic signal strength values also indicate high signal disturbances. Raw signal strength data shown in Figure 8-9 has a typical range of 35 SNR units (dB) with a precision of 0.25 units. Since both GPS frequencies are susceptible to interference there is often a correlation in the shape of the L1/L2 SNR profiles for each satellite. Generally, the SNR profile for the L2 signal will be smoother and lower magnitude than the L1 signal.

8-15. Data Post-Processing

Baseline processing is carried out in steps, starting with raw data as input and finishing with baseline coordinate differences as output. The steps for processing a single GPS baseline are outlined below.

a. Code position. An average absolute position (WGS84) is computed using C/A code pseudoranges and GPS ephemeris data.

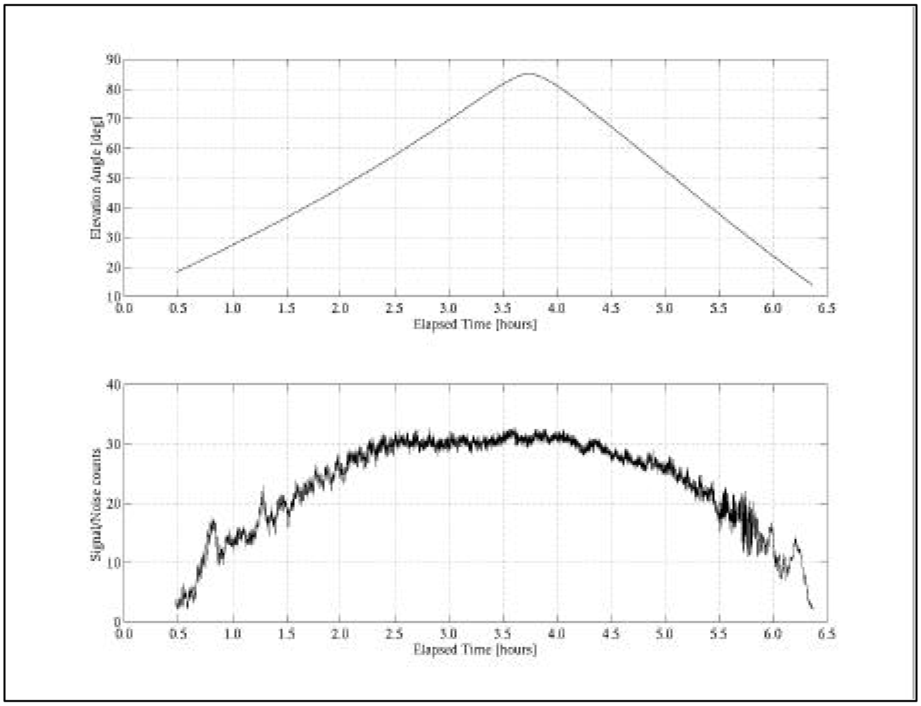

Figure 8-9. Plot of satellite elevation angle and corresponding GPS signal strength profile.

b. Phase differencing. Accumulated L1/L2 carrier phase measurements associated with each GPS satellite are extracted from the two separate raw GPS data files (one file for each GPS receiver). Simultaneous L1/L2 phase measurements from each receiver are differenced to create single difference (SD) data. Differencing the SD data between pairs of satellites forms double differences (DD). The double differencing scheme can be carried out in various combinations of the satellites that were tracked during the observing session. A typical DD scheme involves taking one satellite as a reference and then differencing it against all others remaining. The resulting DD data is then differenced once more, over consecutive time epochs, to form a triple difference (TD). The purpose of differencing is to simplify the GPS observation equations mainly by canceling specific common errors in each receiver's data. Several types of GPS biases are highly correlated and are eliminated by double differencing. For example, satellite orbit errors, and satellite and receiver clock biases are canceled completely. Refraction and signal propagation delays created during transit through the earth's ionosphere and troposphere are minimized.

c. Cycle slip detection. Triple difference data eliminates the so-called "integer ambiguity", a nuisance parameter that exists for each satellite-receiver combination. The ambiguity parameter can be pictured as the unknown number of whole carrier cycles that were in transit when logging began at the receiver station. This value is a constant offset (i.e., number of cycles) which needs to be determined by the software for high accuracy carrier phase processing. One use of TD datasets is to detect cycle slips. Because ambiguities are constant over time, triple difference data will not carry them because TD is a time difference. If the signal tracking process experiences cycle jumps during data collection, then they will be revealed as a large spike in the TD dataset. The cycle slip height on the TD curve roughly corresponds to the number of cycles (in meters) that were skipped. Any detected cycle slips are corrected by re-aligning the phase data by whole cycles to create a smooth continuous curve as a function of time.

d. Float solution. A first run double difference solution uses pre-processed GPS data that was corrected for any cycle slips. This float solution resolves the initial cycle ambiguities into real-valued quantities, and then computes an approximate baseline solution. Ambiguities in the float solution are processed as un-rounded decimal cycle counts assigned to each satellite-receiver pair.

e. Fixed solution. Since the number of cycle ambiguities is known to be an integer value, the float ambiguities are rounded or fixed to the nearest whole number. If the real-number float value is very close to an integer then the rounding is done with high confidence. Fixed solutions will increase the math model accuracy compared to the float solution. Different possible combinations of integer ambiguity values are estimated for each satellite-receiver pair and the best-fit combination is determined by statistical testing. Re-processing GPS data with the correct integer ambiguity values will result in a double difference fixed ambiguity baseline solution.

f. Statistical evaluation. GPS baseline processing results are analyzed after a fixed DD solution is obtained. Typical processing outputs include a separate time series of DD residuals for each receiver-satellite DD pair (i.e., for each measurement epoch). Global measures of solution quality are reported as solution statistics, such as, the data adjustment variance factor, the standard deviation and covariance matrix entries for each baseline component, and fixed to float solution variance ratios.

g. Network adjustment. After the GPS data has been processed a set of baseline solutions will connect the network of monitoring points. All post-processed solution vectors are then adjusted using least squares network adjustment software. The first adjustment is made using minimal constraints, i.e., only the coordinates for one reference station are held fixed, which permits the user to examine the internal errors within the network. Once the first adjustment has been edited to remove outlier measurements, the coordinates of each stable reference station are fixed for the final adjustment. The resulting geodetic coordinates for each monitoring point in the network defines its 3D position.

8-16. Post-Processing Statistics

a. General. Statistics are used to assess processing output and position solution quality, especially with respect to random errors, measurement residuals, and the overall solution fit to the data. Some of the most critical parameters to check after each post-processing session are described below.

b. Double difference residuals. Both L1 and L2 phase measurements will produce DD residuals from the baseline processing adjustment. The following statistics and descriptors for each series of DD residuals are checked to reveal possible low quality data.

(1) Shape of residuals. Measurement errors that contain only random error will be distributed according to the normal probability density function (PDF). Histograms of GPS DD residuals compared with an assumed normal PDF will indicate skewness or systematic error in the data. DD residual time-series profiles vary between satellite pairs and each pair should be visually examined for large deviations from the mean or any kinds of regular patterns in the residual values that might reveal systematic error. Clean data will have a zero-mean (horizontal line) profile containing high frequency random noise (Figure 8-10). An obvious systematic error in a DD residual plot does not mean data quality for that satellite pair is bad. An error trend in one residual series can sometimes show up belonging to the other satellites in view because the solution itself has been biased to an incorrect value as a result of math correlations. A possible reason for this is the GPS software assigning a greater weight to biased data, and because of incorrect assumptions made in its pre-set internal data weighting criteria. Signal quality and session status criteria, independent of math correlations, are recommended for guiding interpretations about the shape of DD residuals. See also Figure 8-11.

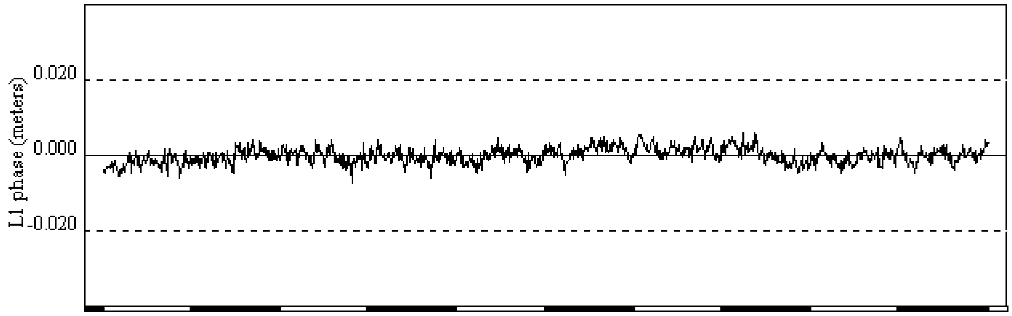

Figure 8-10. An example of GPS (L1) double difference residuals taken from baseline processing demonstrates a typical profile for relatively clean data.

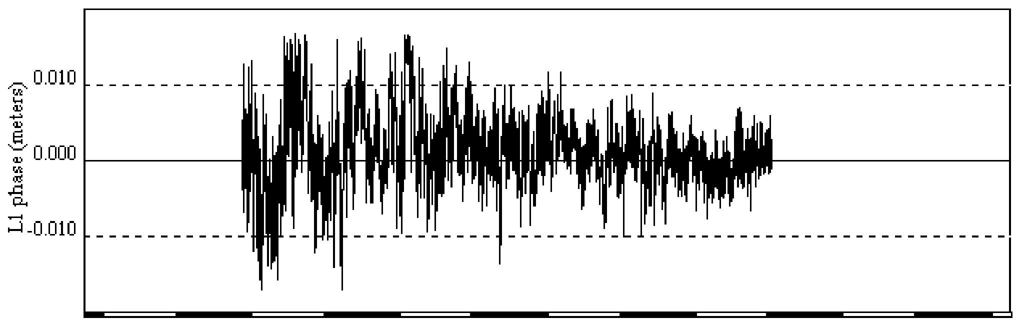

Figure 8-11. An example of double difference residual taken from GPS baseline processing showing effects on L1 signal as satellite rises. Residuals become smaller with time and with higher elevation angle.

(2) Mean value of residuals. Double difference residuals will not be exactly equal to zero even with the highest quality data. Slight shifts in the mean value (less than 5 mm in normal data) are evident in most processing results. If the mean values of several different DD residuals are shifted in the same direction (plus or minus), then this may indicate a low frequency bias in the data. This trend is seen when double differencing involves one reference satellite where its associated biases are mathematically correlated with other SVs. A mean shift less than 3-5 mm indicates good data (however this must be true on all satellites), a shift of 5-10 mm or more usually indicates the presence of measurement bias.

(3) Standard deviation of residuals. The standard deviation (unbiased RMS) of the DD residuals specifies the level of random error in the phase data. Signal noise components, time variable correlations, session length, and GPS processing techniques determines the standard deviation of the DD residuals. Each satellite pair can be ranked according to its RMS value. A standard deviation greater than 4 mm is a cutoff value for identifying poor data. Although standard deviation itself is not sensitive to bias, a large standard deviation can indicate trouble with GPS signal quality.

(4) L1/L2 residuals. Signal disturbance in the local antenna environment is identified by inspection or cross-correlation of L1 and L2 DD residuals (Figure 8-12). With anti-spoofing (A/S) full wavelength L2 data is not directly recovered by P(Y) code-stripping in receiver tracking channels. An L1/L2 cross-correlation or squaring processes is used to reconstruct L2 carrier from its L1 difference (i.e., with respect to L1). Largely similar (L1/L2) DD residual profiles indicates the corresponding recovery

correction term must be relatively constant (or linearly related). This indicates L2 is experiencing the same signal effects as L1. If two (L1/L2) residual profiles are largely different, then the L1 and L2 signals deviate by a significantly variable difference term, and L1/L2 signals are subject to separate external influences. If the L1/L2 profiles are highly correlated, then the signals are behaving the same.

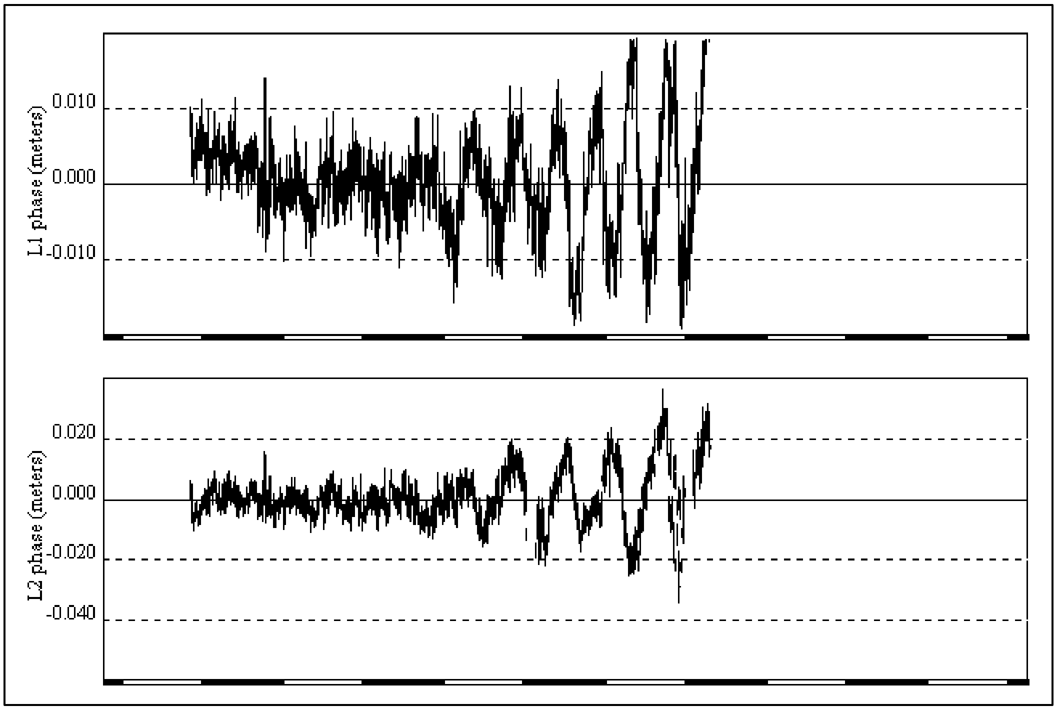

Figure 8-12. Comparison between L1 (above), and L2 (below), double difference residuals taken from GPS data corrupted by multipath.

(5) Reference satellite. Double differencing GPS data can be carried out under different combinations of satellites. A common DD scheme is to select one high elevation satellite to be the reference and then differencing its data from all others. Biases in the reference satellite data will show up in the residual profiles of non-reference satellites because of math correlation. Most baseline processors do not give the user an option to select or change reference satellites. If the processor will allow the user to select the DD scheme, then each satellite's data can be differenced between "neighboring" satellites to lower DD math correlations.

c. Fixed and float solution. The RMS ratio between fixed and float solutions (variance ratio) is an output statistic used to describe the amount of confidence held in the fixed solution. High ratio values (greater than 7 and up to 40 or above) indicate the fixed solution ambiguity is far better than the next best solution ambiguity. Values near one (1) indicate the need for closer examination of the GPS data for quality problems. Only fixed solutions should be accepted for GPS monitoring surveys. Float solution data should be edited, using data quality indicators as a guide, until a fixed solution is obtained. Correct estimates of ambiguity parameters are critical for high accuracy positioning over short baselines, especially for kinematic solutions to prevent excessive data dropouts. The software can accept incorrect ambiguities at a given statistical confidence level. Normally, a float solution will result if the integer ambiguity search does not converge below a set confidence threshold. Float solutions can be addressed first by increasing the number of allowed processing iterations in the software.

d. Cycle slip counts. PLL filtering bandwidth limits signal tracking to a set frequency range. Large transient shifts in input can exceed PLL tracking design. These events create difficulty maintaining accurate signal phase lock. Signal disturbances falling within the PLL tracking range can still cause cycle slips because the PLL only discriminates 2π phase shifts. If tracking skips any number of whole cycles (0.5% of data or less is nominal), then it is possible for the PLL to re-acquire phase lock at the new locus of phase well before the next measurement cycle arrives. Any detected cycle slips indicate periods of rapid change in signal dynamics, which implies lower phase tracking and measurement resolution.

e. Adjustment variance factor. Formal errors are directly influenced by the observation residuals through the a-posteriori variance factor. This is a scalar quantity with an expected value equal to one (1.0). The variance factor is used to scale random error as reported in the parameter covariance matrix. Values more than one indicates an overly optimistic weighting scheme was applied to the measurements. Values less than one indicate an overly pessimistic observation weighting scheme. GPS observing sessions will typically have a variance factor greater than one because physical and mathematical correlations have been ignored. Values more than 3-5 indicate the need for closer examination of the GPS data for quality problems.

f. Adjustment covariance matrix. The covariance matrix of parameters is an upper triangular (symmetric) matrix containing the precision values for ΔX, ΔY, and ΔZ baseline components. The variance of each coordinate component is found along the matrix diagonal. The statistical correlation (covariance) between coordinate components is defined by the off-diagonal elements. Covariance matrix entries are used to determine and report absolute and relative positioning error ellipses. GPS covariance matrix values should be less than 1×10^{-6} for baselines used on monitoring networks. The covariance matrix that is output from baseline processing is used to weight the baseline coordinate differences during network adjustment.

g. Error ellipses. A standard output from the baseline processing adjustment is the confidence ellipse (or error ellipse). An error ellipse graphically (and geometrically) portrays the region of positioning uncertainty associated with the adjusted coordinates at a given statistical confidence level. Absolute or point error ellipses apply only to individual stations. Relative error ellipses apply to the baselines between two stations. Both types are based on the entries in the covariance matrix of parameters. The largest dimension of the error ellipse is called the major semi-axis. Its length indicates the maximum expected position error at a selected confidence level (usually 95 percent). The semi-major axis of the point ellipse is compared with the positioning accuracy requirements established for the project. If the value is greater than the allowed position error, then the survey does not meet the design specification. Generally this will not be the case because error levels reported by baseline processing are often much too optimistic. GPS error ellipses can be oriented toward a particular direction (azimuth) indicating greater uncertainty in those position components.

8-17. Closure and Station Checks

a. Baseline misclosures. Loop misclosures are computed by comparing at least four inter-connected baselines. Point misclosures are computed from at least two reference stations and one monitoring point on the structure. Closures that are statistically different from zero indicate potential bias in the data. Misclosures are automatically smoothed to an average value for the baseline component in the network adjustment. A test on the sample mean (i.e., position) is used to assess bias in misclosures. Baselines with misclosures greater than 5 mm are candidates for further quality checks. Any three baselines connected in a triangle will contain only one misclosure value, but two different point misclosure schemes can be checked.

(1) Reference station ties. For production surveys only short (15-30 minute) observing sessions are made between any three points (two reference stations and the monitoring point on the structure). Each reference station is fixed with coordinates from higher accuracy surveys based on collecting many hours of data just between the two reference stations. The first type of misclosure assessment uses only the baseline computed between the reference stations. A test on the mean for position change is made using the long and short GPS sessions between the two reference stations. Coordinate components from each session are differenced and tested against an expected value of zero. A test on the variance is used to assess coordinate precision. A design standard deviation of 1.44 mm can be used as the expected precision for each coordinate component to ensure positioning is below 5 mm at 95 percent.

(2) Monitoring station ties. The second type of misclosure assessment compares the two baselines from each reference station to the monitored point. A test on the mean is made on the misclosure between each reference station baseline and the mean position of the monitoring point computed using both baselines. This second test will indicate the combined position change at the monitored point derived from both reference stations. Fixing the average adjusted position of the monitored point allows for inspection of short session data propagated back to each reference station. The position change at each reference station can then be examined. If there are problems with only one particular reference station (during the short session), then its raw data should be examined further and either cleaned or the station de-weighted before processing the final network adjustment.

b. Code positions. Processing code positions at each station can be done separately to investigate the statistics of the code data. Although code positioning results will not be used to monitor the structure, data quality for each station and each satellite can be checked. Code measurement time delays are especially well-related to signal quality. In the TEQC software, an MP (code multipath) parameter is extracted from code solutions to indicate the relative amount of multipath on each satellite code range.

c. Kinematic position solution. Static GPS data can be forced to process as a kinematic time series of positions. Kinematic positions are in some ways more easily inspected and reviewed for quality than the static session. One test used to identify poor quality kinematic data is to compute an expected phase error based on the RMS of the signal strength data coming from each satellite. The expected phase error is determined at each measurement epoch and then ranked in increasing order. This process is repeated for each satellite-receiver combination, so that the signal strength RMS is again ranked in increasing order between satellites. If there are time periods of more than several minutes at each receiver where the RMS is consistently below two (2) for at least five (5) satellites, then these will generally represent higher quality data blocks. RINEX file editing with user-developed software can extract and process the signal strength data. Re-processed results should be checked against the unedited kinematic solution time series. Only slight improvements should be observed in position output.

d. Multipath detection. SNR profiles and DD residuals can be inspected for the presence of multipath by comparing their deviation profiles. To recover these profiles, L1/L2 SNR values can be extracted from RINEX files, and DD residuals for each satellite pair are output from the processing adjustment. A multipath signature is verified by comparing the shape (deviations) of the SNR profile to each double difference residual series at corresponding time epochs for both L1 and L2 frequencies. They will show similar trends and relative amounts of deviation if systematic error is present. This is true with multipath because it affects both L1/L2 signal frequencies in a similar manner.

Section IV
GPS Multipath Error

8-18. Description of Multipath Signals

a. General. GPS signal interference is a major source of systematic error in GPS monitoring surveys. Multipath signals are a predominant cause of interference in GPS carrier phase measurements over short baselines. This section describes the characteristics of multipath signals as a source of error in precise baseline determination.

b. Properties of multipath signals. Multipath signals are an unavoidable operational trait of the GPS system in obstructed environments and will occur repeatedly under the right conditions.

(1) Data correlation over sidereal day. The GPS satellite constellation occupies the same position in orbit with respect to the earth once every sidereal day. A GPS sidereal day differs from a standard solar day by approximately four minutes less each day (i.e., about 23-hrs 56 min). If the local antenna environment is unchanged and the antenna remains stationary, then multipath reception will be repeated over two consecutive sidereal days. In practice, this behavior is not perfectly repeatable due to variable signal reception, noise power levels, orbit or atmospheric changes, and it assumes similar equipment, data collection, and processing procedures. Inspection of double difference residuals over consecutive days can verify the presence of multipath (Figure 8-13). Auto-correlation of the double difference residuals for satellite pairs observed over consecutive days can estimate the time shift more precisely than inspection.

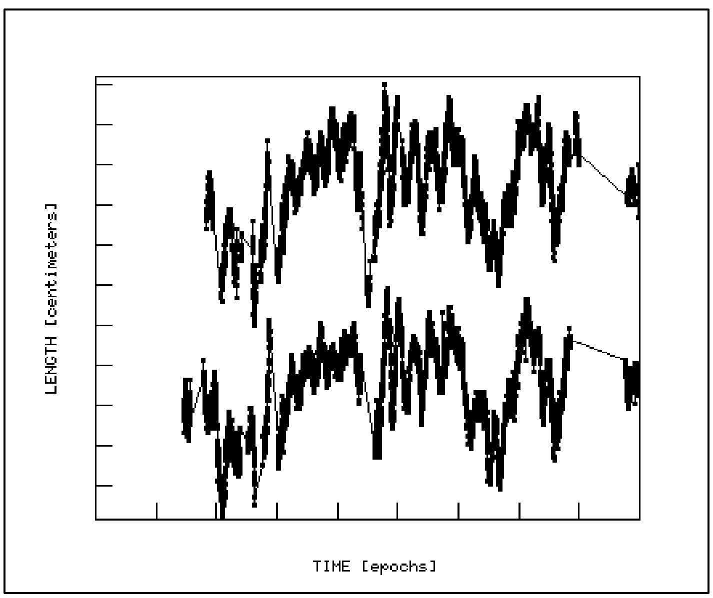

Figure 8-13. GPS (L1) double difference residuals from sessions separated by exactly one sidereal day showing correlation of multipath errors.

(2) Reflector distance dependence. Large phase errors can occur with small changes in antenna-reflector distance. At L1/L2 wavelengths, a change in distance of only 5 cm can produce a maximum phase error of 90 degrees (i.e., 1/4 of L1 wavelength). As GPS satellites move in orbit with respect to the receiver, signals may strike different reflectors and travel along different paths to the antenna. A time-

varying multipath signal is then expected to occur based on path difference between direct and reflected signals. A simple geometric model describes this interference at the antenna site.

$$\phi / d \sin(\theta) = 2\pi / \lambda \qquad \text{(Eq 8-6)}$$

Phase difference (ϕ) depends on path length difference between direct and reflected signal paths, and a path length difference of one (L1 or L2) wavelength (λ) corresponds to a phase difference over one complete wave cycle (2π). Dependence of phase on reflector distance from this ratio is:

$$\phi = (2\pi/\lambda)\, d \sin(\theta) \qquad \text{(Eq 8-7)}$$

where

ϕ = phase difference
λ = wavelength
d = antenna-reflector distance
θ = angle of incidence

characterizes the geometric relationship of phase and reflector distance for multipath signals.

(3) Dependence on signal frequency. The duration of multipath in GPS data will vary with signal frequency. Figure 8-14 shows a characteristic profile for the time period of L1/L2 multipath signals. Long-period multipath is a major difficulty in GPS data because its resulting bias is absorbed into the baseline solution as a position offset. Since multipath is not expected to be correlated between different satellites, detection of low frequency bias can be attempted by inspection of raw GPS data. Figure 8-14 shows that reflectors close to the antenna will most adversely affect GPS signals.

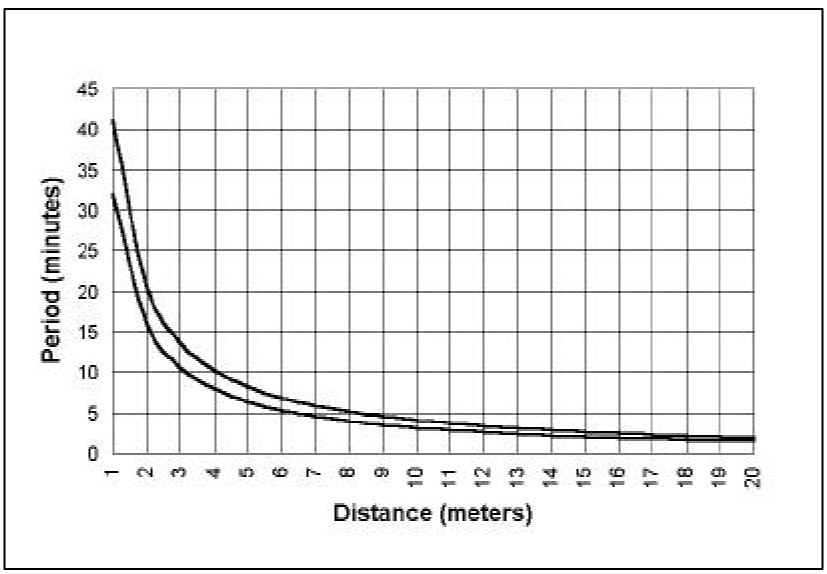

Figure 8-14. Plot of theoretical multipath period against reflector distance for L1 and L2 GPS signals. GPS L1 frequency is modeled in the lower curve.

(4) Session length dependence. Multipath can persist from a few minutes to several hours based on distance to the reflector. Sampling at least one complete interference wavelength eliminates long period multipath by averaging its effects by additive and subtractive phase cancellations. Session lengths less than 30 minutes would have to have a minimum antenna separation of 1.5 meters from surrounding reflectors (see Figure 8-14).

(5) Signal strength variations. A basic characteristic of EM waves is that energy is propagated in a direction perpendicular to the surface of uniform phase. Changes in signal phase are coupled to changes in signal strength through the interference phenomena produced by multipath. Inspection of observation double difference residuals show an empirical correlation to associated signal strength values. Both types of data have a quasi-cyclic patterned profile in receiver-to-satellite data contaminated by multipath. In the context of code phase DGPS applications a simple relationship exists between phase variance and signal-to-noise ratio (SNR) as in, for example, Omega system receivers. An empirical SNR value calculated from phase variance could be used as a measure of expected signal strength deviation in GPS data. Recovery and reporting of SNR observables from GPS receivers currently lacks specification in RINEX format observation files, due in part by the fact that GPS product manufacturers are not obligated to provide SNR values, or may provide them in a reduced or proprietary format without background details about their source.

(6) Satellite elevation angle dependence. Multipath has a greater chance of occurring and surviving to reach the antenna from low elevation satellites. This is because multipath signals are less likely to experience multiple bounces, and because antennas do not receive signals equally well in all directions. Low elevation direct signals have lower receive power levels due to antenna gain pattern (lower gain near horizon). Multipath then has relatively higher signal power compared to low elevation direct signal power. Partial multipath rejection can be built into the antenna by shaping the antenna gain pattern (choke ring antenna) or increasing the mask angle.

8-19. Data Cleaning Techniques for GPS Surveys

a. General. Several different strategies are available for suppressing multipath effects in GPS data. These can be broadly categorized by hardware, environment, and data processing.

b. Modification of antenna environment. Some of the most effective methods for reducing multipath involve blocking the reflected signal before it is sensed by the antenna.

(1) Source modeling. A proposed multipath reduction strategy is to exploit the dependence of multipath on site geometry and to calibrate its effects using detailed maps of reflections in the antenna environment. Creating a topographic site model that accurately predicts multipath signal propagation would be difficult if the nature of local reflectors is highly variable, giving rise to numerous complicated signal interactions. If there are only simple sources of reflection at each station, then the modeling process would need to be repeated for many different station occupations. Processing corrections for multipath interference based on site geometry are not yet generally practical for GPS.

(2) Choke ring antennas. Specially designed choke ring antennas are manufactured to enhance attenuation of surface waves traveling along the surface of the antenna. Choke ring antennas have a series of precisely sized concentric metal collars mounted on top of the ground plane that serve to attenuate surface waves on the ground plane caused by ground reflections under the antenna. Choke ring antenna are not generally useful for stopping reflections coming from above the antenna, such as from vertical walls, rooftops, etc.

(3) Antenna placement. A universal technique for reducing multipath is to place the antenna in a low signal reflection environment. This is probably the most important requirement for reducing effects of multipath in GPS carrier phase data. Even smaller objects and trees near the station (up to several to tens of meters) can produce significant multipath interference. Site reconnaissance is essential for selecting premium locations for GPS stations.

(4) RF absorbent ground planes. Certain high performance materials have applications in reducing multipath reflections. Sheets or blocks of radio frequency absorbent foam are placed around the antenna and/or antenna mount. These have been tested to partially intercept and attenuate multipath and other EM interference in the local antenna environment, but still should be considered as a specialized approach for dealing with multipath.

c. Robust GPS observing strategies. Optimizing the session observing conditions and enhancing the likelihood of collecting large amounts of uncorrupted GPS data can reduce multipath effects.

(1) Session length. GPS performance over specified session lengths is described in Section II. Increased session length tends to randomize the periodic signature of multipath bias. If the GPS session length is greater than the total period of the error signal, then the phase deviations will have a more uniform distribution about the mean. A one-second sampling rate should be used mainly for the purpose of data inspection and quality control. Actual processing of longer station occupations with 5-10 second data rates usually provides the same mean baseline solution.

(2) Data redundancy. Redundant measurements provide checks on the GPS data and increases overall reliability of the survey. Several different applications of redundancy can be applied on GPS monitoring surveys.

(a) Multiple reference stations. Measurements from multiple reference stations can be used to improve positioning accuracy. More accurate positioning is obtained by collecting data at each monitoring station with more than one baseline tie. Well connected survey configurations create sub-networks that robustly tie each monitoring point to the reference network.

(b) Multiple station occupations. Multiple sessions and occupations can be used to improve positioning accuracy. GPS data logged under different observing conditions causes systematic errors to tend to cancel when repeated baseline solutions are averaged. Surveys with extremely short observation windows (1-5 minutes) should be re-occupied several times (separated by at least one hour).

(3) Continuous monitoring. Monitoring sessions that span multiple days can use data stacking techniques. Double difference residuals associated with repeated daily measurements (for example over one week) are added together to recover a correlated multipath signature. Cross-correlation will magnify systematic error that can be isolated from random error in the residuals.

d. Kinematic solution processing. Kinematic data processing schemes are well-suited for selective data editing because position outputs are reported at each logging epoch (e.g., one second). The objective in kinematic solution post-processing is to select the highest quality data for re-processing. Averaging only clean GPS data and eliminating poor quality data improves final position accuracy. Data quality indicators can be used to identify periods of corrupted or less reliable data. The relative data quality for every epoch in the position output series is ranked and then combined into continuous blocks that represent the best data. Common GPS data quality indicators are presented in Section III. This process can be defeated in cases where undetected systematic errors have been absorbed into the baseline solution. It is important to use data quality indicators that provide independent information about potential systematic error. Signal strength values and session status parameters are likely to be better sources for position weighting models than residuals. A data quality hierarchy should be used to clean and reprocess kinematic data. For example, eliminate satellites that have discontinuous phase tracking, then low elevation satellites, and then data with low signal strength or erratic deviations in signal strength. In practice, signal strengths below about 20 dB (out of a range of 30-40 dB) start to be unreliable. These editing schemes are analogous to weighting schemes that can be applied directly to the phase data.

8-20. Mandatory Requirements

There are no mandatory requirements in this chapter.