STATIC GLOBAL POSITIONING SYSTEM SURVEY DESIGN AND SOURCES OF ERROR IN SUBSIDENCE INVESTIGATIONS

Marti E. Ikehara (U.S. Geological Survey, Sacramento, California)

A Global Positioning System (GPS) survey is most successful when the geometric qualities of the satellite configuration and the receiver network are maximized, and the occurrence and magnitude of systematic and random errors are minimized. By late 1992, there were 21 GPS satellites in 6 orbital planes around Earth, contributing to a period (window) of 7 consecutive hours during which radio signals from 4 or more satellites could be simultaneously observed by receivers. The ideal GPS satellite geometry occurs when the satellites are widely dispersed overhead in each of the 6 orbital planes, throughout the duration of the observation period. The optimal time of day and maximum length of the observation period is dependent on the location of the study area and number of fully operational (healthy) satellites visible at that location.

Designing the pattern of station occupation is a function of the number of receivers available and the amount of redundancy required. For a static GPS survey, the ideal configuration of the loops composed of vectors between stations is circular rather than linear. Vectors should also be relatively similar in length to reduce the sensitivity of the error component of the computed values that is proportional to length. The control stations must be observed a minimum of twice and preferably thrice. Stations most important to the objectives of the GPS survey should also be reobserved. Requirements for different levels of high-precision GPS-survey classifications and detailed guidelines for designing networks to achieve the required level of accuracy can be found in Federal Geodetic Control Committee (1989).

Knowing the speed of radio waves, the distances between several satellites and one receiver can be calculated by timing the interval between transmission and reception of a ranging code carried on the signal. The three-dimensional position of a station on Earth is trilaterated from the knowledge of these distances and of the locations of the satellites within each orbit. The subsidence investigator is primarily interested in the measurement of the vertical position of a station. The ellipsoidal height is the GPS-determined vertical coordinate of a station and is referenced to an ellipsoid, currently Geodetic Reference System (GRS) 80, which approximates the Earth's shape. A closer approximation of the local vertical reference system (datum) is achieved by modeling the difference between the ellipsoid and the geoid, or mean sea level, which is the basis for the vertical datum. Surface gravity and conventional leveling measurements are used to contour the geoidal separations. These relations are expressed by $H = h - N$, where H is the land-surface elevation, referenced to mean sea level, h is the ellipsoidal height, and N is the geoidal separation (fig 1). By convention, when the geoid surface is below the ellipsoid surface, as it is in North America, N is negative. When the land surface is below the geoid (sea level), for example at Death Valley, California, both H and h are negative. When the land surface is above the geoid but below the ellipsoid, H is positive but h is still negative.

For subsidence monitoring, differences in ellipsoidal heights over a period of time at a station can be equated to changes in its vertical position. To compare a station's current vertical position with historic measurements, the geoidal separation, N, must be determined and used to calculate a GPS-derived elevation which is then compared with spirit-leveled elevations. The accuracy of N over the conterminous United States, compared with leveling, ranges from 10-cm root mean square (RMS) at 100-km distances between stations, to 1-cm RMS at 10-km separations (Milbert, 1991a). The inaccuracy of N is the largest source of error in GPS calculations of H.

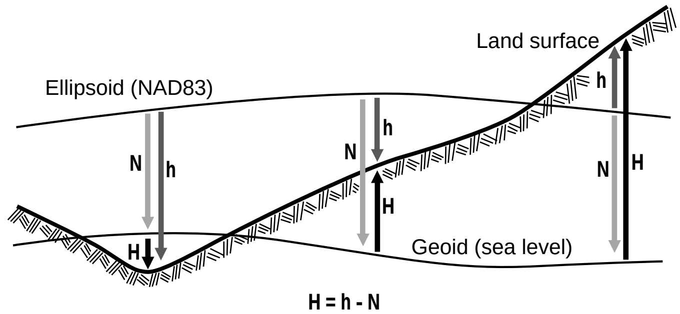

Figure 1. Three possible relations among land-surface elevation, ellipsoidal height, and geoidal separation for a bench mark in North America.

There are two horizontal and two vertical datums currently in use nationally, and there can be local-agency datums as well. The selection of a set of horizontal control stations and a set of vertical control stations (bench marks), each referenced to a single horizontal or vertical datum, respectively, defines the three-dimensional reference system to which GPS vector coordinates are converted. A GPS network for subsidence investigations must have control stations, especially those defining the vertical datum, that are not susceptible to land subsidence. Bench marks suitable for control are those that have been leveled at the same time originally and later show no change in elevation when releveled in several years or decades.

The quality of a set of measurements is defined by its precision, which is the degree of agreement of repeat measurements, and its accuracy, which is the degree of agreement with the true value, the difference of the latter comparison being termed bias. GPS measurements are corrupted by systematic error, which can be either constant in value and thus additive, or proportional, often relative to vector length. Measurements are also subject to random errors that result from variable, usually uncontrollable, observing conditions. Systematic errors are usually minimized by designing a good network and observing schedule. Postprocessing techniques are sometimes effectively used to reduce random errors by correcting or eliminating bad observations.

Although GPS signals are known to bend and slow while traveling through the troposphere (0–10-km altitude), this source of timing error is not significant in the southwestern United States or for vectors less than several tens of kilometers (Dixon, 1991). In environments with low relative humidity, degradation of satellite signals is most severe in the ionosphere (~50–500-km altitude), where ionic activity is proportional to solar radiation. Making GPS observations at night greatly minimizes signal speed corruption resulting from normal atmospheric conditions and the 11-year-cyclical sunspot activity (both systematic error sources) and from extreme solar activity (random error). Because the time delay that radio waves experience when traveling through the ionosphere is frequency dependent, the signals on the L1 (Coarse Acquisition- or Precise(P)-code) and L2 (codeless or P-code) carriers of dual frequency receivers can be compared to estimate the time delay and then correct the calculated distances for ionospheric effects.

Multipathing, another systematic error, occurs when the same signal is detected several times at the antenna after being reflected. This error can be eliminated by choosing locations without reflective surroundings, proper antenna height positioning, and observing for several hours to average out the effect. Additionally, signals below a horizon of 10 to 20º can be filtered out during postprocessing to reduce errors due to both multipathing and atmospheric refraction of low-angle signals.

Random errors can be resolved only during postprocessing. Noise in the carrier-phase (and rarely in the code-phase) observables, the major random error source, results in cycle slips, interrupting the tabulation of carrier-phase full-wavelength cycles. Cycle slips can be detected graphically and corrected manually. Glitches in signals can result from temporary mechanical failures in satellites, lightning and severe weather or solar activity, and cellular telephone interference. Other random errors result from careless or incorrect execution of field procedures. Differences resulting from imprecise centering and leveling of the antenna over the same station on different occupations are examples of small random errors. An operator error nearly impossible to correct is the incorrect measurement or recording of the height of the instrument, or antenna, above the measurement point of the station.

With careful planning and execution, the horizontal and vertical coordinates of stations in a network can be accurately measured by GPS surveying in support of land-subsidence monitoring.