APPENDIX C — ELEVATION SURVEYS

Vertical Datums.

In 2001, the American Society for Photogrammetry and Remote Sensing (ASPRS) published a manual entitled: "Digital Elevation Model Technologies and "Applications: The DEM Users Manual." Chapter 2 of this manual provides an excellent reference on vertical datums. It explains reasons why the North American Vertical Datum of 1988 (NAVD 88) has replaced the obsolete National Geodetic Vertical Datum of 1929 (NGVD 29). NGVD 29 was based on an erroneous assumption that mean sea level at 26 tidal gauge sites all represented the same (zero) elevation. Furthermore, NGVD 29 benchmarks throughout the U.S. suffered from an accumulation of relative errors, exceeding 1.5 meters in some locations.

NAVD 88 is the only official vertical datum of the U.S., and it is best suited for GPS surveys that yield *network accuracies*. However, the NSRS still includes many NGVD 29 benchmarks that were surveyed with differential leveling and have never been rigorously surveyed with GPS to establish accurate ellipsoid heights.

For any point on the Earth being surveyed with GPS, the *ellipsoid height* is the height above or below the WGS84 reference ellipsoid, i.e., the distance between a point on the Earth's surface and the WGS84 ellipsoidal surface, as measured along the normal (perpendicular) to the ellipsoid at the point and taken positive upward from the ellipsoid. Defined as "h" in the equation: $h = H + N$ (see Figure C.1).

The *geoid* is that equipotential (level) surface of the Earth's gravity field which, on average, coincides with mean sea level in the open undisturbed ocean. In practical terms, the geoid is the imaginary surface where the oceans would seek mean sea level if allowed to continue into all land areas so as to encircle the Earth. The geoid undulates up and down with local variations in the mass and density of the Earth. The local direction of gravity is always perpendicular to the geoid.

What we call the *elevation* on a FEMA EC is technically its *orthometric height*. The *orthometric height* is the height of a point above the geoid as measured along the plumbline between the geoid and a point on the Earth's surface, taken positive upward from the geoid. It is defined as "H" in the equation: $H = h - N$ (transposed from the above equation).

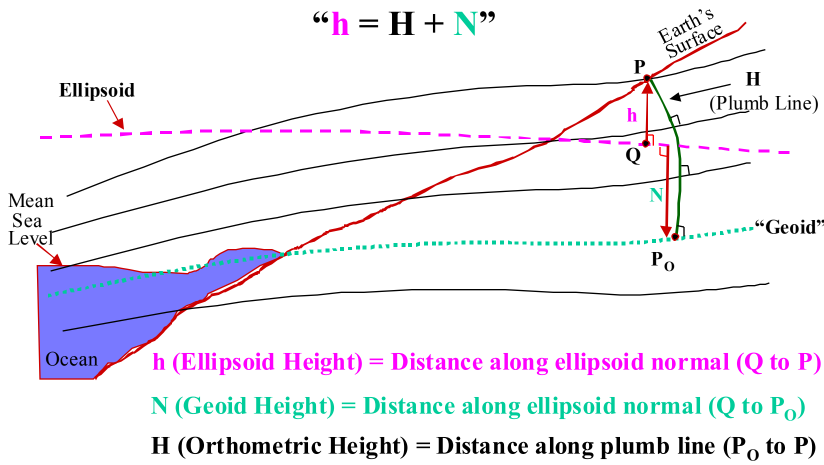

Figure C.1 — Relationships between Ellipsoid, Geoid*, and Orthometric Heights

* In the U.S., "N" is a negative number because the geoid is below the ellipsoid, making this formula (h = H + N) correct, although it appears in the above example to have its algebraic sign reversed. Throughout much of the Earth elsewhere, the geoid is above the ellipsoid.

Differential Leveling. Differential leveling establishes a horizontal line-of-sight that is perpendicular to the direction of gravity. Differential leveling follows the rules of gravity, and all elevations are above the geoid. Differential leveling has traditionally been the most common way to determine differences in elevation between points A and B, between points B and C, between points C and D, and on and on using multiple surveyors with diverse instruments over many decades of time until the last surveyor arrives at a theoretical final benchmark somewhere in the U.S. and calculates the elevation as __ ft above mean sea level, assuming point A was at mean sea level with zero elevation. The accuracy of each benchmark is *relative* to the accuracy of each of the preceding benchmarks surveyed enroute to the theoretical final benchmark. Furthermore, the elevation at the theoretical final benchmark is dependent upon the route surveyed, because of variations in the slope of the geoid along different routes; thus different elevations can be surveyed for the same point when using differential leveling simply by following different routes to the final destination (the final benchmark). Although these differences are insignificant for short distances surveyed, they accumulate and become significant over large distances. Furthermore, differential leveling does not provide geographic coordinates (latitude and longitude). When approximate latitude and longitude are required, a map is usually scaled to estimate these coordinates; when accurate latitude and longitude are required, GPS procedures are the preferred option.

GPS Surveying. Whereas traditional surveying follows the rules of gravity, GPS surveys follow the rules of geometry. The GPS surveyor does not establish elevations (orthometric heights) directly, but indirectly, because GPS yields *ellipsoid heights* which are converted into *orthometric heights* (elevations) by applying the latest geoid model from NGS which models the *undulation of the geoid* (the Geoid Height "N" in the above formula, i.e., the distance of the geoid below the ellipsoid in the U.S.) at any given latitude and longitude. NGS' latest geoid model is Geoid 03, released in January, 2004.

GPS surveys best support *network accuracy* because they are most easily tied to CORS stations that are used to define the geodetic datum defined by WGS84. Furthermore, GPS surveys always yield accurate latitude and longitude values.

National Spatial Reference System (NSRS). NOAA's National Geodetic Survey (NGS) defines and manages the National Spatial Reference System (NSRS) -- a consistent coordinate system that defines latitude, longitude, height, scale, gravity, and orientation throughout the U.S. NSRS comprises a consistent, accurate and up-to-date network of continuously operating reference stations (CORS) which support 3-dimensional positioning activities, a network of permanently marked survey points (monuments and benchmarks), and a set of accurate models describing dynamic, geophysical processes that affect spatial measurements.

The accuracy and accessibility of NSRS is dependent on contributions of GPS or leveling observations by state, local, and private surveyors. Survey data must meet rigorous "bluebook" standards and achieve minimum accuracies of first-order horizontal or second-order vertical, with accuracies verified using NGS-approved software.

NGS Data Sheets are available nationwide from the NSRS at www.ngs/noaa.gov. These Data Sheets include 6-digit Permanent Identifiers (PID numbers), name stamped on the monuments, latitude and longitude based on the NAD 83 horizontal datum, elevations (orthometric heights) based on the NAVD 88 vertical datum, geoid height, ellipsoid height, horizontal order and class, vertical order and class, stability, station descriptions (to-reach directions) and station recovery information.

Because these NSRS monuments and benchmarks are considerably more accurate and stable than FEMA's elevation reference marks (ERMs), NSRS monuments are mandatory as GPS base stations from GPS land surveys as well as airborne GPS surveys for photogrammetry, LIDAR and IFSAR.

National Height Modernization Study. In 1998, NGS contracted with Dewberry to prepare the "National Height Modernization Study, Report to Congress." This report documented the advantages of GPS over traditional differential leveling and provided recommendations for modernizing the National Height System in the U.S. based on GPS. The recommendations of this study are now being implemented, and Height Modernization surveys are now in progress nationwide that will further serve to improve the ability of GPS surveyors to routinely establish *network accuracies* of 5-cm and *local accuracies* of 2-cm and 5-cm when specified survey procedures are followed. On behalf of NGS, Dewberry is currently researching and revising these specifications in NGS-58.