

National Height Modernization:

Cost comparison of conducting a vertical survey by leveling versus by GPS in western North Carolina

Introduction:

The North Carolina Geodetic Survey (NCGS) conducted a National Height Modernization Study (NHMS) to compare the accuracies and staff-hour costs of elevations determined by traditional leveling versus by using Global Positioning System (GPS). The study was conducted in western North Carolina near Asheville, because this region experiences crustal motion. Similar cost comparison studies were conducted as part of the National Height Modernization program in northern and southern California in areas also experiencing crustal motion as well as subsidence. These cost-comparison studies were funded by the National Height Modernization program to determine if GPS surveys could link the nation's vertical geodetic network at a sufficient accuracy and with significant cost savings compared to traditional leveling surveys.

The National Height Modernization (NHM) program was established to update the vertical component of the existing spatial geodetic reference framework, which has had many geodetic monuments destroyed by development and compromised by seismic and subsidence activity. This spatial geodetic reference framework ties our country together with precise and universally accepted coordinates of location and elevation on the earth, which is critical for safe and efficient construction, transportation, navigation, and numerous other applications. The importance of this information framework can be best explained in the graphical comparison (Figure 1) showing the seamless flow of a well constructed freeway built with all the construction teams using the same, accurate coordinates versus an imaginary bridge being built with construction teams using different and inaccurate coordinates (NGS, 1999).



Figure 1. A graphical demonstration of the importance of an accurate and universally accepted spatial geodetic reference network. Left image: The seamless flow of a well constructed freeway that was built with all the construction teams using the same, accurate coordinates. Right image: An imaginary bridge being built with construction teams using different and inaccurate coordinates.

(http://www.ngs.noaa.gov/PUBS_LIB/thePossibilities/Imagine_all.pdf)

The spatial geodetic reference framework was constructed and maintained by the Coast and Geodetic Survey branch of the U.S. Department of Commerce, which later became the United States Coast and Geodetic Survey (USC&G), and which is currently known as the National Geodetic Survey (NGS). Until very recently with the advent of GPS in 1987, NGS relied on using traditional, line-of-sight survey measurements between physical reference points even as technology advanced from telescopic levels to modern laser levels (Figure 2). In a laborious and time-consuming process, a system of more than a million reference points was built by survey crews taking geodetic measurements about every hundred yards to form the nation's geodetic reference framework (NGS, 1998).



Figure 2. Conventional line-of-sight survey methods that have changed very little from the leveling survey party in the left image (<http://www.photolib.noaa.gov/historic/c&gs/theb1773.htm>), which used a telescopic level similar to the center image (<http://www.surveyhistory.org/index.htm>), to present-day leveling survey parties, which utilize laser levels similar to the Zeiss level in the right image (<http://www.zeiss.com/survey/digital/dini11.shtml>).

However with the advent of GPS in 1987, the survey world and other positional applications have been forever changed. Although GPS was developed by the U.S. military for military applications, the sales of GPS equipment and services for all non-military applications is projected to soon dwarf the military applications (Figure 3).

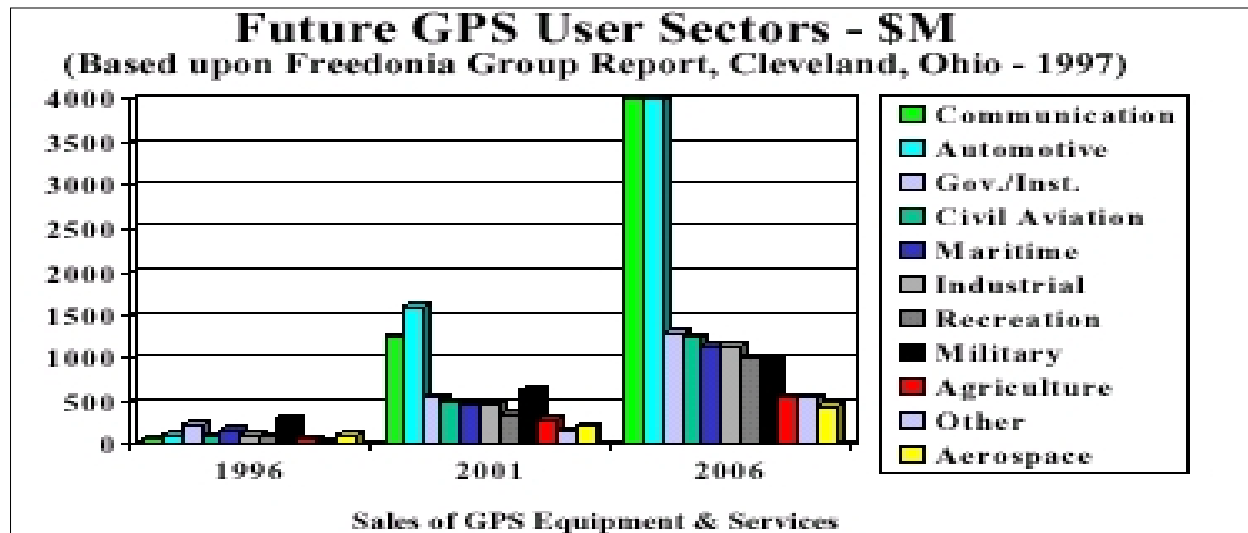


Figure 3. Sales chart (millions of dollars) of GPS equipment and services for different user applications from 1996 to projected levels in 2001 and 2006 (<http://www.survmap.org/height rpt.html>).

GPS (Figure 4) is a constellation of 28 satellites, which transmit radio signals that can be received by GPS receivers worldwide. This system is a tremendous asset to geodetic positioning, because GPS surveys can be accomplished without having intervisible stations (i.e. stations that can be seen from another point) and is not constrained by distance or terrain. Furthermore, navigation users can navigate with GPS independent of seeing physical landmarks. By using GPS, a survey that once took days to complete by traditional leveling methods can now be done in a fraction of the time and at a fraction of the cost.



Figure 4. The global positioning system (GPS). Left image: Composed of 28 satellites orbiting the earth at 20,200 km (<http://www.colorado.Edu/geography/gcraft/contents.html>). Center image: A Trimble GPS receiver and antenna (<http://www.trimble.com/products/pdf/geosurvey.pdf>). Right image: GPS navigation is independent of physical landmarks (<http://www.colorado.Edu/geography/gcraft/contents.html>).

NGS and state geodetic agencies, such as NCGS, provided the infrastructure (GPS base stations, database of station coordinates and elevations, and geodetic software) that facilitate both public and private civilian applications of GPS. In addition, NGS coordinated with state geodetic agencies to establish the High Accuracy Reference Network (HARN), which is a highly accurate, underlying geodetic control network that allows many diverse civilian applications of GPS technology (NGS, 1998).

Despite the booming sales of GPS technology (Figure 3), GPS's potential for innovative applications beyond traditional uses has yet to be fully exploited. This contradiction is because the utilization of GPS has progressed in two stages. During the formative years of GPS, the system was more accurate in determining horizontal coordinates than in determining vertical heights due to: (1) the limited number of satellites (i.e. the constellation was built-up over the course of several years); (2) limited orbital information; and (3) early stage geoid and atmospheric models. GPS has entered into its second stage with a full satellite constellation, better orbital information, more refined geoid and atmospheric models, and with guidelines on determining elevations entitled, "Guidelines to Establishing GPS-Derived Ellipsoid Heights" (Version 4.3, 2 cm Standard) (NOAA, 1997). These guidelines describe the standards, specifications, and techniques developed by NGS in cooperation with the GPS community that enable GPS to attain the accuracy levels required for most height-based applications. Unfortunately, these techniques are not yet commonly known nor practiced by the private-sector surveying community. Consequently, it would require a major technology transfer effort to introduce these techniques on a widespread basis (NGS, 1998).

Most importantly, and the crux of the National Height Modernization program, the existing geodetic reference framework that supports height measurements is outdated and must be modernized. Our nation's geodetic framework is unable to fully support the use of GPS to determine accurate height measurements and therefore unable to facilitate GPS height dependent applications (NGS, 1998).

Fortunately, this out-dated network is being replaced. The modernized NGS satellite-based National Spatial Reference System (NSRS) is replacing the existing time-consuming, labor-intensive framework with a significantly smaller network designed to support and enhance the technological advantages of GPS. NSRS maximizes the potential of GPS by enabling GPS methods to determine height measurements to the accuracies required for their respective applications, as well as bridging the gap between GPS and pre-existing reference systems. In addition, NSRS is easier to maintain and 10 to 100 times more accurate in the horizontal dimension than the previous system (NGS, 1998).

In many respects NSRS can also be thought of as the foundation for the National Spatial Data Infrastructure (NSDI), a critical component of the "information superhighway." NSDI facilitates data sharing by organizing and providing a structure of relationships between producers and users of spatial data and thus ensures consistent and reliable means to share spatial data (NGS, 1998).

NGS has recently completed the major portion of the horizontal component of NSRS. However, the vertical component of NSRS, the National Height System (NHS), will be more difficult to modernize than the horizontal component. Because, urbanization and construction have destroyed many of NHS's component geodetic monuments and because many of its monuments have been compromised by subsidence and seismic activity (Figure 5).

Figure 5. A dramatic example of subsidence in California showing the drop in land elevation from 1925 to 1977 (<http://water.usgs.gov/pubs/circ/circ1182/pdf/06SanJoaquinValley.pdf>).

As a result, the system is unreliable in many areas and nonexistent in other areas. Until recently, only conventional vertical surveying methods could be used to implement NHS due to accuracy requirements. Fortunately, the recent development of NGS technical guidelines and techniques (NOAA, 1997) now offers the prospect that GPS can be used to accomplish the modernization effort at a much lower cost (NGS, 1998).

NGS has established the National Height Modernization Study (NHMS) to fund research projects studying the need and benefits of a modernized NHS; the potential and existing GPS applications that could be supported by a modernized NHS; and the technical, financial, legal, and economic aspects of using GPS technology to modernize NHS. It is this latter research topic of the economic aspects of using GPS technology to modernize NHS that this cost comparison study by NCGS fulfills.



Materials and Methods:

NCGS conducted a National Height Modernization Study (NHMS) to compare the accuracies and staff-hour costs of elevations determined by traditional leveling versus using GPS. The study was conducted in western North Carolina in Buncombe County (Figure 6), because this region experiences crustal motion. The project extended from the downtown area of Asheville, North Carolina to the Eastern Continental Divide, which is approximately 32 kilometers (km) east of Asheville (NGS, 1998).

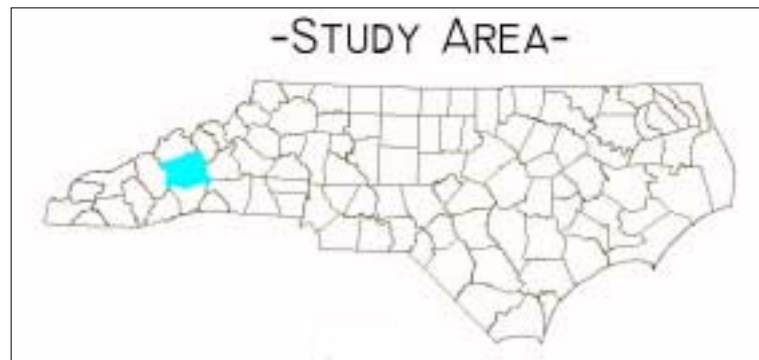


Figure 6. The project study area in Buncombe County, North Carolina.

The leveling route was 60 km in length. The average difference of elevation between sections was 14 meters with the maximum difference being 54 meters. Section lengths averaged 0.75 km and leveling was performed to Second Order Class I specifications. All new sections were double run. Leveling was performed with a Jena NI005A compensator optical precision leveling system with a built-in micrometer, a Zeiss NI-2 compensator with an attached micrometer, and four Kern GK-23E invar rods. In addition, NGS turning pins and thermistors were used (NGS, 1998).

The GPS surveys (NGS, 1998) were performed with four Trimble 4000SSE and two Trimble 4000SSI dual frequency GPS receivers using L1/L2 geodetic antennas with ground planes. Fixed height poles were used at all times except at the Continuously Operating Reference Station (Base Station PID AA5552). The GPS data was processed with GPSurvey (Version 2.3) using the precise ephemeris. The adjustment of the GPS data was performed with the NGS adjustment program "ADJUST." The "Guidelines to Establishing GPS-Derived Ellipsoid Heights" (Version 4.3, 2 cm Standard) (NOAA, 1997) were followed and Geoid96 was used to obtain geoid heights.

Comparison of GPS and Leveling:

A free adjustment was performed holding one bench mark (E 39, PID FB0803, First Order Class I) and one HARN (K 180 PID FB0035) fixed. The elevations obtained from this adjustment were compared to the published elevations of benchmarks occupied with GPS and with the adjusted elevations obtained from the leveling performed in this project. The average difference between the GPS and leveling orthometric heights was -0.015 meters with the largest difference being -0.031 meters. The largest differences occurred in the eastern area of the project near the Eastern Continental Divide. The results of this project indicate that GPS can obtain 2-5 centimeter heights at the 95% confidence level when proper field procedures and a good geoid model are utilized (NGS, 1998).

The results of this project indicate that GPS can obtain 2-5 centimeter heights at the 95% confidence level when proper field procedures and a good geoid model are utilized.

Project Statistics:

The project statistics are presented in Table 2.

Table 2. Project Statistics.

Elevation Survey Type	Station Type	Number of Stations
GPS	Total number of stations occupied	39
	Existing horizontal	11
	Existing vertical stations	3
	Existing horizontal with vertical	12
	GPS stations established	13
Leveling	Total number of stations occupied	81
	Existing vertical stations	41
	New vertical stations	40

Time Comparison (GPS vs. Leveling):

The time comparison did not include the staff hours for reconnaissance for either the GPS phase nor the leveling phase, because mark recovery/setting was required to perform both GPS and leveling. Please note that although the reconnaissance time for GPS differed slightly from the time for leveling, there was no difference in time statistically. In addition, geodetic marks found along the level route were positioned vertically as is consistent with NCGS standard practice. Yet, positioning these additional marks in the leveling phase did not affect the comparison of staff hours between geodetic leveling and the GPS observations (NGS, 1998).

The staff hour comparisons between leveling and GPS are presented in Table 1. This table reported that the GPS survey took 27% less time than the comparable leveling survey, which can be rephrased to state that the staff-hour cost to conduct an elevation project by GPS was 73% less than by conventional leveling (NGS, 1998).

Table 1. Time comparison (staff hours) between elevations determined by leveling (2nd Order Class I) versus by GPS (2 cm Standard).

Component of Elevation Survey	Time (Staff Hours)	
	Leveling (2nd Order Class I)	GPS (2 cm Standard)
Field Observations	1,111	282
Computations	25	25
Total	1,136	307

The staff-hour cost to conduct an elevation project by GPS was 73% less than by conventional leveling.

Summary:

This study compared the cost of completing an elevation survey by methods (GPS vs. traditional leveling) that generally use incomparable cost indexes. GPS surveys estimate costs by the number of points surveyed (\$/point). Whereas, leveling surveys estimate costs by the kilometer (km) distance leveled (\$/km). This dilemma was overcome in this study by comparing the staff-hours used completing each elevation survey, since both elevation surveys covered the same exact area.

Each type of surveying (GPS or traditional leveling) has its advantages and disadvantages. Traditional leveling provides greater accuracy than GPS. Therefore, it is the method-of-choice in projects requiring height determinations at the sub 2 cm level. In addition, traditional leveling is more cost efficient than GPS in small distance projects where vertical control is very close together, such as along beaches.

In contrast, GPS is more cost efficient in large distance projects, because GPS costs remain constant with distance. Whereas, leveling costs increase with distance. Therefore once a project size increases beyond the small project size (~1 km), GPS is more cost efficient than traditional leveling. Furthermore, this cost savings increases with project distance (Figure 7).

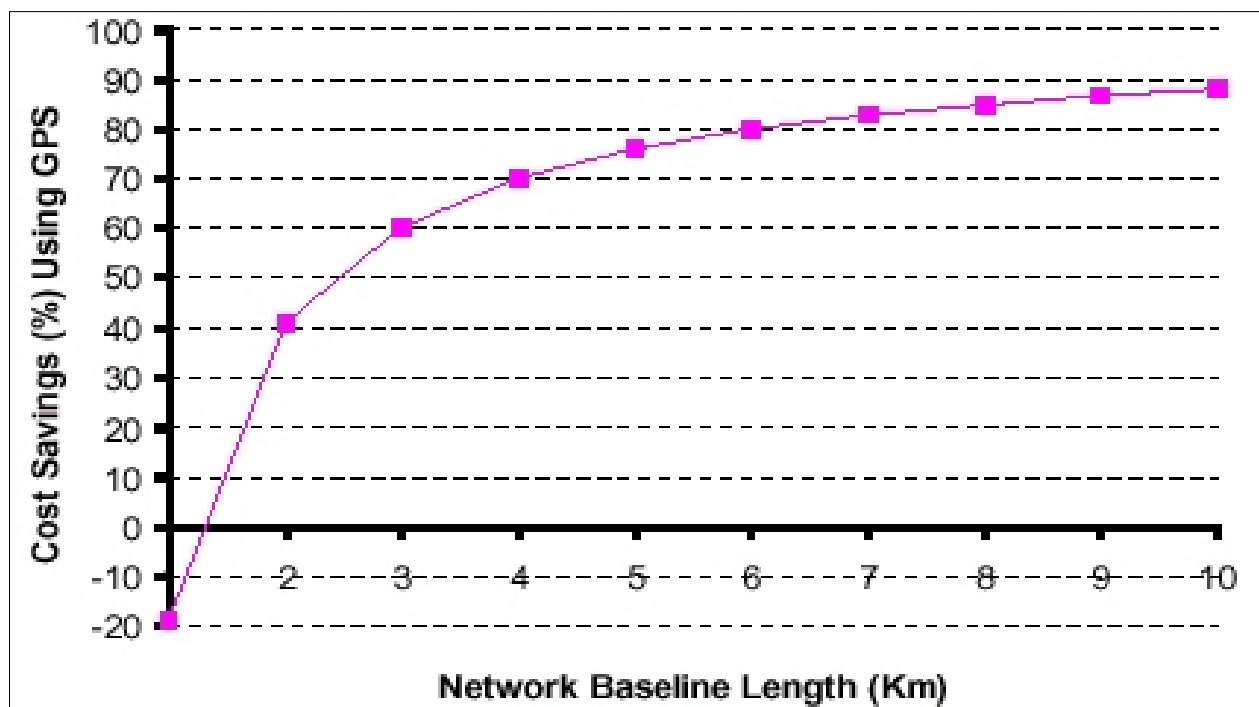


Figure 7. Cost savings (%) by network baseline length (km) in determining elevations by GPS instead of by traditional leveling (<http://www.survmap.org/heightcpt.html>).

GPS has the additional advantage over traditional leveling by being independent of the terrain surveyed. This terrain independence means that there is no difference in GPS surveying whether the baseline is level or extends into mountains. Whereas, leveling costs increase significantly in hilly or mountainous terrain relative to flat terrain.

In review, both GPS and traditional leveling have their advantages and disadvantages with regard to accuracy, cost efficiency, and terrain independence. More precisely, these advantages and disadvantages are project specific (Table 2).

Table 2. GPS vs. traditional leveling comparison for accuracy, cost efficiency, and terrain independence.

Survey Type	Accuracy	Cost Efficiency	Terrain Independence
GPS	Above 2 cm	Large distances (>1 km)	Yes
Traditional Leveling	Sub 2 cm	Small distances (< 1 km)	No

If the project objectives were to map a small, flat area to a high level of accuracy then traditional leveling would be the method-of-choice. Yet, the project objectives of the National Height Modernization program are to link the NHS of the entire United States of America, which is a large, vertically diverse, and even discontinuous area. Therefore, the method of choice to link the NHS network nationwide would need to be by GPS.

GPS is the method-of-choice to link the National Height System network nationwide, because it provides sufficient accuracy and is cost efficient over large distances and vertical diverse landscapes.

Using the results from this study in North Carolina with the results from the California cost comparison studies, NGS estimates that an NHS network (point spacing of 10 km) constructed by GPS could save 88% in costs and 94% in time relative to constructing the network via traditional leveling (NGS, 1998).

GPS could save the nation 88% in costs and 94% in time linking the National Height System network as compared to linking the network via traditional leveling.

Literature Cited:

- National Geodetic Survey. 1998. National Height Modernization Study: Report to Congress. Washington, D.C. Retrieved on May 18, 2000 from the World Wide Web: <http://www.survmap.org/heightrpt.html>
- National Oceanic and Atmospheric Administration. 1997. Guidelines For Establishing GPS-Derived Ellipsoid Heights (Standards: 2 cm and 5 cm) Version 4.3. Retrieved on May 20, 2000 from the World Wide Web: http://www.ngs.noaa.gov:80/PUBS_LIB/NGS-58.html