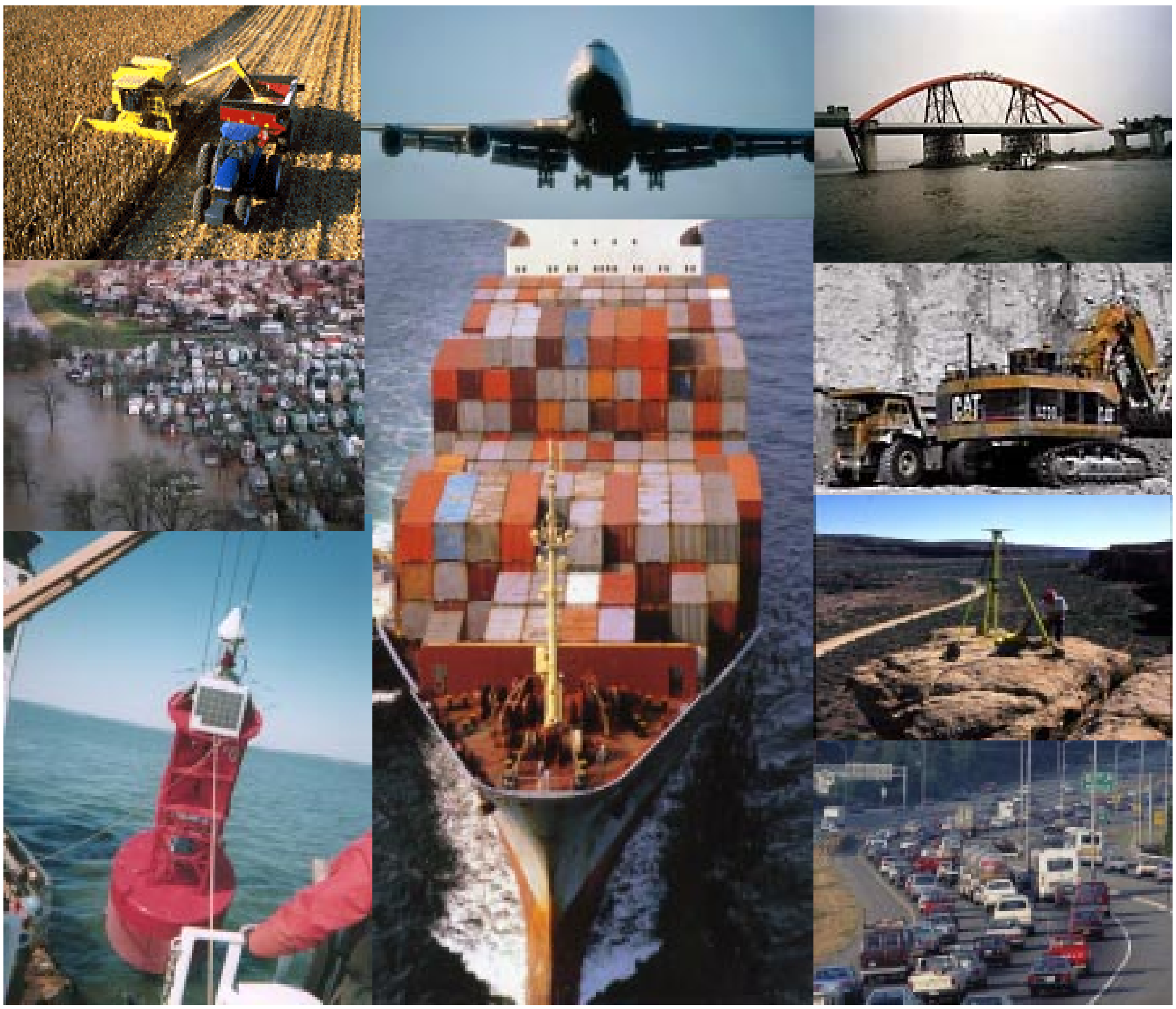
National Height Modernization Study

Report to Congress



U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
National Ocean Service
National Geodetic Survey

June 1998

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GLOSSARY

ANA	Area Navigation Approach
ASPRS	American Society for Photogrammetry and Remote Sensing
AVL	Automatic Vehicle Location
BARD	Bay Area Regional Deformation
B/C	Benefit/Cost
BFE	Base Flood Elevation
BLM	Bureau of Land Management
BMP	Best Management Practice
CAD	Computer Aided Dispatch
CADD	Computer Aided Design and Drafting
CAES	Computer Aided Earthmoving System
CALTRANS	California Department of Transportation
CBN	Cooperative Base Network
CFT	Controlled Flight into Terrain
CORS	Continuously Operating Reference Station
C&GS	Coast & Geodetic Survey
DATIS	Digital Airborne Topographic Imaging System
D&D	Dewberry & Davis
DEM	Digital Elevation Model
DGPS	Differential Global Positioning System
DLG	Digital Line Graph
DOC	Department of Commerce
DOD	Department of Defense
DOT	Department of Transportation
DTED	Digital Terrain Elevation Data
DTM	Digital Terrain Model
DFIRM	Digital Flood Insurance Rate Map
EOM	Earth Observation Magazine
EPA	Environmental Protection Agency
ERIM	Environmental Research Institute of Michigan
ERM	Elevation Reference Mark
FAR	Federal Acquisition Regulation
FBN	Federal Base Network
FBS	Federal Base System

FEMA	Federal Emergency Management Agency
FGCS	Federal Geodetic Control Subcommittee
FGDC	Federal Geographic Data Committee
FHA	Federal Housing Administration
FIRM	Flood Insurance Rate Map
FIS	Flood Insurance Study
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FRA	Federal Railroad Administration
GIS	Geographic Information System
GPS	Global Positioning System
GWEN	Ground Wave Emergency Network
H&H	Hydrologic and Hydraulic
HARC	Houston Advanced Research Center
HARN	High Accuracy Reference Network (Horizontal Control)
HAZMAT	Hazardous Material
HGCSD	Harris-Galveston Coastal Subsidence District
HPGN	High Precision Geodetic Network
IFMRC	Interagency Floodplain Management Review Committee
IFSAR	Interferometric Synthetic Aperture Radar
IFSARE	Interferometric Synthetic Aperture Radar for Elevation
IMU	Inertial Measuring Unit
ISTEA	Intermodal Surface Transportation and Efficiency Act
ITRF	International Earth Rotation Service Terrestrial Reference Frame
ITS	Intelligent Transportation System
JPL	Jet Propulsion Laboratory
KHZ	Kilohertz
LAAS	Local Area Augmentation System
LF/MF	Low Frequency/Medium Frequency
LIDAR	LIght Detection And Ranging
MARAT	Method, Accuracy, Reliability, and Application Test
MLLW	Mean Lower Low Water
MSL	Mean Sea Level
MWD	Metropolitan Water District
NAD 27	North American Datum of 1927 (Horizontal Datum)
NAD 83	North American Datum of 1983 (Horizontal Datum)
NAPP	National Aerial Photography Program
NASA	National Aeronautics and Space Administration

NAVD 88	North American Vertical Datum of 1988
NCGS	North Carolina Geodetic Survey
NDGPS	Nationwide Differential Global Positioning System
NFIP	National Flood Insurance Program
NGS	National Geodetic Survey
NGVD 29	National Geodetic Vertical Datum of 1929
NHS	National Height System
NIMA	National Imagery and Mapping Agency
NOAA	National Oceanic and Atmospheric Administration
NOS	National Ocean Service
NPS	National Park Service
NRCS	Natural Resources Conservation Service
NSDI	National Spatial Data Infrastructure
NSF	National Science Foundation
NSRS	National Spatial Reference System
NTSB	National Transportation Safety Board
NYSDEC	New York State Department of Environmental Conservation
OSTP	Office of Science and Technology Policy
P&A	Psomas & Associates
PDD	Presidential Decision Directive
PGGA	Permanent GPS Geodetic Array
PDC	Positive Train Control
PID	Permanent Identifier (ID Number)
PPS	Precise Positioning Service
PTL	Positive Train Location
PTS	Positive Train Separation
QA/QC	Quality Assurance/Quality Control
QBS	Qualifications Based Selection
RMS	Root Mean Square
RMSE	Root Mean Square Error
RTK	Real Time Kinematic
S/A	Selective Availability
SCIGN	Southern California Integrated GPS Network
SDWA	Safe Drinking Water Act
SFHA	Special Flood Hazard Area
SPS	Standard Positioning Service
TEC	Technical Evaluation Contractor (FEMA)
TEC	Topographic Engineering Center (U.S. Army)

TIN	Triangulated Irregular Network
UCLA	University of California Los Angeles
UDN	User Densification Network
URISA	Urban and Regional Information Systems Association
USACE	U.S. Army Corps of Engineers
USBR	U.S. Bureau of Reclamation
USCG	U.S. Coast Guard
USC&GS	U.S. Coast & Geodetic Survey
USFS	U.S. Forest Service
USGS	U.S. Geological Survey
VLBI	Very Long Baseline Interferometry
V-Zone	Velocity Wave Action (Flood Zone)
WAAS	Wide Area Augmentation System
WGS	World Geodetic System
WHP	Wellhead Protection Program
WHPA	Wellhead Protection Area

EXECUTIVE SUMMARY

Introduction

This document was prepared in response to the direction contained in House Report 105-207 (to accompany H.R. 2267 - Departments of Commerce, Justice, and State, the Judiciary, and Related Agencies Appropriations Bill, Fiscal Year 1998) that the National Geodetic Survey "*conduct a National Height Modernization Study to demonstrate the effectiveness of this work in California and in western North Carolina. The Committee expects the NGS to conduct this study in consultation with state and local governments and the private sector*." The results of the study, as abstracted by this Executive Summary, present not only a compelling argument for the need to modernize the vertical component of the National Spatial Reference System, but also demonstrate how the Global Positioning System can be used to accomplish the modernization effort with significant cost savings.

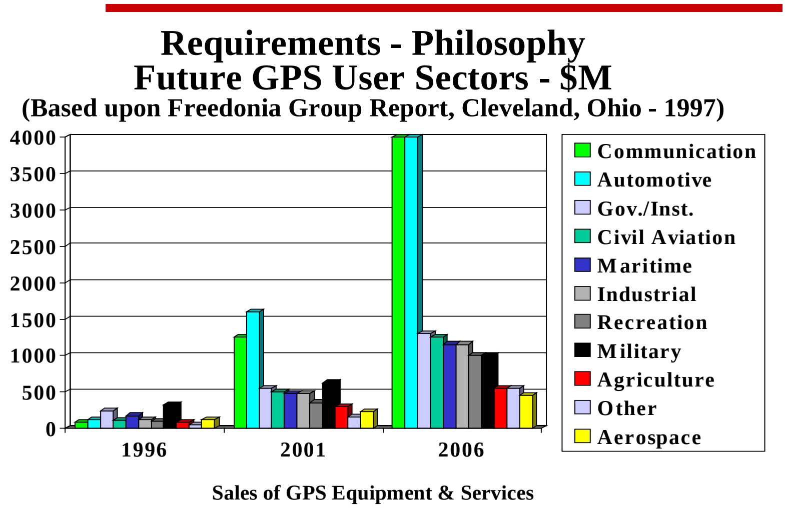
> The National Geodetic Survey is an office within the National Ocean Service, which is a subset of the National Oceanic and Atmospheric Administration, a bureau within the United States Department of Commerce.

A Revolution in Traditional Surveying

Though most of us are not familiar with the science of geodesy, the world around us is full of examples of its importance to our lives and our nation's prosperity. The safety and efficiency of the buildings we live and work in, the roads and bridges we drive on, and the trains, airplanes, and ships that carry the products we use every day all depend on a universally compatible system of geodetic reference points that tie our nation together. Geodesy is the basic ability to determine the location of a particular point in three-dimensional space, and to accurately relate it to another point. It is a fundamental necessity that underlies almost every facet of how the world functions today.

The mission of NOAA's National Geodetic Survey (NGS) is to ensure that the United States has the consistent, high-accuracy geodetic reference framework it needs to support these fundamental activities. Until recently, NGS has relied on using conventional line-of-sight survey measurements to provide that framework through a network of physical reference points accessible to users throughout the nation. Conventional leveling methods required crews of geodetic surveyors to have literally walked from border to border and coast to coast, carrying surveying equipment and taking geodetic surveying measurements every hundred yards or so, to establish and maintain a national coordinate system accessible to all users. In this fashion, a system of more than a million reference points was eventually built and serves today as the nation's geodetic reference framework.

The advent of the Global Positioning System (GPS), however, has irreversibly transformed this landscape. Developed by the U.S. military, GPS is a constellation of 24 satellites that transmit their signals to receivers all over the world. GPS enables geodetic positioning to be accomplished without having to physically see between points. Using GPS, a survey that once took days to complete can now be done in a few hours at a much lower cost. GPS has also introduced the fourth dimension of time, enabling more accurate modeling of the earth's crustal motion. In addition, GPS techniques have enabled "real-time" positioning applications. As a result, GPS has not only revolutionized the traditional civilian navigation, surveying, and mapping professions, but has spawned numerous new applications in industrial sectors not previously dependent on geodesy. GPS has quickly become critical to our nation's technological leadership and competitiveness in today's global economy.



America's Global Positioning System (GPS) *already is* the world's next Utility System. The Freedonia Group and similar organizations project a meteoric rise in GPS users over the next decade, with communications, automotive and other applications impacting virtually every American.

The U.S. Department of Defense established and maintains the constellation of GPS satellites. NGS uses GPS to provide a more accurate, underlying geodetic coordinate system that makes possible and supports the many diverse civilian applications of GPS technology. NGS provides the infrastructure that facilitates public and private civilian applications of GPS. However, GPS's potential for innovative applications beyond traditional uses has yet to be fully exploited.

This is because the utilization of GPS has progressed in two stages. Initially, GPS was much more accurate in determining horizontal coordinates than vertical heights due to a number of technical factors. It is only recently that standards, specifications, and techniques have been developed, primarily by NGS in cooperation with the GPS community, that enable GPS to attain the accuracy levels required for most applications utilizing height information. Unfortunately, these techniques are not yet commonly known or practiced by the private-sector surveying community, and require a major technology transfer effort to introduce them on a widespread basis. In addition, the existing geodetic reference framework that supports height measurements is outdated and must be modernized. It is unable to fully support the use of GPS to determine accurate height measurements and therefore enable the substantial benefits possible through GPS height dependent applications.

The modernized NGS satellite-based National Spatial Reference System (NSRS) is meeting that challenge by replacing the existing time-consuming, labor-intensive framework with a significantly smaller network designed to support and enhance the technological advantages of GPS. The modernized NSRS is easier to maintain and 10 to 100 times more accurate in the horizontal dimension than the previous system. 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 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 has recently completed the major portion of the horizontal component of NSRS by leveraging appropriated funding through other Federal, state, and local government entities. However, the vertical component of NSRS, the National Height System (NHS), presents a bigger challenge to modernize. Urbanization and construction have destroyed many of the original reference survey points that NHS is founded upon, and numerous others have succumbed to the effects of subsidence and seismic activity. As a result, the system is unreliable in many areas, and nonexistent in others. 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 now offers the prospect that GPS can be used to accomplish the modernization effort at much lower cost.

This study assesses the need(s) for, and benefits to be derived from, a modernized NSRS/National Height System, and in turn the many existing and potential GPS technology applications it will support. The study also evaluates the technical, financial, legal, and economic aspects of using GPS technology to modernize NHS. The study presents findings, and makes recommendations for their implementation.

Study Scope and Methodology

NGS established the following major goals for the study:

- Identify and document user requirements for height data, including those requirements utilizing both vertical and horizontal data.

- Identify and document major users and applications of the National Height System and GPS-derived height data.

- Identify and recommend the best, most cost-effective actions that meet the documented user requirements, taking into consideration all technologies available.

- Evaluate the estimated costs to implement the recommended actions, and their benefits to the nation.

NGS, with the assistance of private sector consultants, conducted the study to meet these goals by utilizing three main mechanisms:

- Utilization of User Forums and other outreach means to obtain the insights and recommendations of state and local governments, the private sector, and other interested parties to:

    - identify outstanding needs and requirements with respect to height information and technology,

  - assess current and potential applications of the National Height System and GPS height data, and

  - document their value to the nation.

- Determination of the relative costs and benefits of GPS technology versus conventional methods for height surveys by evaluating 16 case studies. This step involved having users conduct post-analyses of pre-existing, ad-hoc GPS height survey projects in California, North Carolina, and other selected locations.

- Determination of the relative costs and benefits of GPS technology versus conventional methods for height surveys by contracting for surveys to be conducted utilizing both methods over identical project areas.

  NGS consultants were responsible for the collection, assessment, analysis and reporting of the information gathered by the above steps for the study.

Study Results

The following summarizes the information gathered through the study's User Forums and cost-benefit evaluations.

User Forums

The most common themes identified by users with regard to unmet needs and requirements for height information, as grouped into broad categories, were:

- The need for a reliable, cost-effective, standardized, legally established national vertical reference datum and the infrastructure (NSRS) through which to access and utilize it.

- The capability to easily inter-relate the many vertical datums currently in existence, but particularly with respect to a standardized national vertical reference datum.

- The need for national technical standards and guidelines for using GPS to determine heights.

- The need for improvements to NSRS, particularly the National Height System component, to improve access throughout the nation, includes:

- implementation of the National Height System network of survey points at a nominal spacing of 10 kilometers by 10 kilometers,
- densification of the GPS Continuously Operating Reference Station network,
- improvements to the geoid models required to relate GPS determined heights to those determined through conventional systems, and
- improved infrastructure support for real-time GPS positioning.

Existing and potential GPS height application themes that were frequently identified by the user community were grouped into five major summary categories:

- Public Safety
- Transportation Management
- Infrastructure Management
- Construction and Mining
- Agriculture and Natural Resources.

The study examined each of these categories and provides in depth assessments of their existing applications, potential applications, and benefits. The study also examined the support provided, or potential benefits that would be realized, for these applications from an accessible National Height System. A cross section of just some of the many benefits include:

- Improved coastal and harbor navigation, enabling safer and more cost-effective shipment of goods.
- More efficient fertilizer and pesticide application, reducing runoff of chemicals that result in water pollution, and enhancing economic competitiveness through lower costs and higher crop yields.
- Accurate digital elevation models, enabling better floodplain analysis and determination of flood insurance needs.

- Enhanced airline and aircraft safety through GPS-controlled approach and landing systems.
- More accurate models of storm surges, coastal erosion, and trajectories of oil and chemical spills that enable better response to these hazards.
- Improved understanding of tectonic movement.
- Better management of natural resources through the use of reliable geographic information systems (GIS).
- Support for the modernization of America's transportation infrastructure and the mission and goals of the Intermodal Surface Transportation and Efficiency Act.
- Accurate and consistent elevation data for building environmentally sustainable cross-border projects with Canada and Mexico.

The study gathered information and assessed the financial benefits, either realized or projected, of the applications identified within the summary categories. As seen on the next page, the potential for financial benefits was found to be staggering, even based on conservative estimates.

Areas benefiting from a modernized National Height System	Estimated Value to Constituents	Explanation of Benefits
Nationwide Terrain	**$33.5 million**	• Replace less-accurate Level 1 DEMs that cost USGS approximately $33.5 Million • Enable rapid generation of contours for USGS maps and GISs nationwide • Enable 3-D modeling by USACE, FHA, FRA, FAA, EPA, USFS, etc.
Nationwide Watersheds	**$100 million**	• Automated hydrologic modeling by NWS and FEMA to predict locations/ volumes of peak water concentrations
Special Flood Hazard Areas (SFHAs)	**$225+ million**	• Automated hydraulic modeling by FEMA to determine depth and extent of flood waters • Determination of flood risks and insurance rates
Coastal Erosion Zones	**$11.25+ million**	• Accurate determination of coastal erosion rates • Determination of insurance rates
Urban Areas	**$500 million**	• Urban planning • Intelligent Transportation System (ITS) planning • Elevation layer in GIS database • Stormwater management
Farm Lands	**$1.7 billion**	• Precision farming for planned application of water, fertilizer, etc. • Control of unwanted run-off and stream contamination
Maritime Navigation and Safety	**$9.6 billion**	• Positioning of dredges • Positioning of cargo ships
Surveying Industry	**Not estimated**	• Vastly improved survey procedures
Totals	**$12+ billion**	•

Table of estimated benefits from a modernized National Height System summarized from several of the Study tables

Case Studies

This step summarizes detailed reports submitted to NGS from users in the field providing data on both the cost benefits and other lessons learned through the use of GPS techniques over conventional surveying methods. A variety of different types of surveying projects were selected to provide a good cross section of applications. Most of the case study GPS surveys were conducted prior to NGS' publication of its GPS height survey guidelines. It was found that:

- The cost savings realized from using GPS versus conventional surveying methods ranged from 25 percent to more than 90 percent, depending upon the type of survey conducted. The large range of cost savings was primarily due to the type of project being conducted. However, these cost savings should be qualified as follows. It is expected that had the more rigorous NGS guidelines been followed, overall cost savings may have been lower, but quality assurance and data reliability would have been much higher. This potential reduction, however, would be offset by the greater efficiencies gained through adherence to established NGS guidelines.

- Cost savings were greatest when large distances (> 4km) existed between survey points, and there was no requirement to establish heights at intermediate points. Cost savings diminish, or are negligible, when distances are small (< 2 km) between survey points.

- When NGS guidelines were followed, GPS-derived heights were accurately determined within the range needed by most users, e.g., 2 centimeters (3/4 inch) for their applications.

- A common, reliable vertical datum (e.g., NAVD 88) that is easily accessible through an existing infrastructure (NSRS/NHS) is essential for the use of GPS-determined heights to be possible and effective.

- Utilizing GPS to conduct a survey has an added benefit of providing horizontal coordinates in addition to height information. Two separate surveys would have to be run using conventional surveying methods to accomplish the same results at obviously much higher cost.

- GPS is particularly effective when geodetic control must be quickly re-established in disaster areas where the local geodetic infrastructure has been largely destroyed, when a project involves large areal coverage, or when difficult, rugged terrain lies between survey points.

- A combination of GPS and conventional surveying methods often makes the most effective use of both.

- The number of primary control points required can often be significantly reduced using GPS techniques.

<u>Variable Cost Savings from GPS</u>

• **Post Hurricane Elevation Surveys**	**90%**
• **Post Earthquake Elevation Surveys**	**66%**
• **Water District Elevation Surveys**	**75%**
• **Crustal Motion Monitoring**	**99%**
• **Subsidence Monitoring**	**45 - 75%**
• **GPS RTK Construction Surveys**	**26 - 71%**
• **County- and City-wide 3-D Control Surveys**	**26 - 80%**
• **Topographic Mapping for Reservoir Construction**	**71%**

Cost Comparison Surveys

Contracts were let in North Carolina and California to survey the same survey points (within each contract) by first using one method, and then repeated using the other method (GPS technology and conventional surveying), to determine the relative differences in costs, accuracies, and other factors under controlled conditions, including being run using NGS guidelines. It was found that:

- The contract surveys confirmed the significant cost savings and desired accuracy level results found in the case studies, as well as the other additional benefits identified by the case studies. The cost savings are discussed in more detail below.

- In general, conventional surveying methods are more accurate than GPS methods for height determination over relatively short distances. However, at the 10 kilometer spacing recommended for the National Height System, GPS accuracies are comparable with those attained by conventional surveying for most applications.

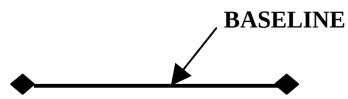
- One of the surveys highlighted an additional benefit of utilizing GPS to determine heights. A difference in the results obtained by the two methods identified the need to refine the geoid model (used to convert GPS-determined heights to those determined by conventional methods) for the local area. This benefit will be realized for other areas if GPS methods are used to implement the National Height System.

Comparison of GPS versus conventional surveying costs are best discussed in terms of survey points connected and the distance in between those points. Within reason, the distance between survey points is not a cost factor for GPS, but is a major factor for conventional surveying methods.

In general, survey points that are relatively close together (< 3 km) can have their heights determined for less cost by using conventional methods over GPS methods (although GPS also provides horizontal coordinates at no additional cost). However, once this minimum distance is exceeded, cost savings from using GPS methods rapidly accrue. Because GPS costs essentially remain constant for two survey points (within reason), the greater the distance between survey points, the larger is the savings. The following tables are based on an analysis of the results of the contract surveys.

The first table shows cost comparisons assuming a survey conducted between two points and an increasing distance. GPS methods result in cost savings somewhere between 2 and 3 kilometers.

For two points connected by a single baseline with lengths between 1 and 10 kilometers, the comparative costs between leveling and GPS are shown below.

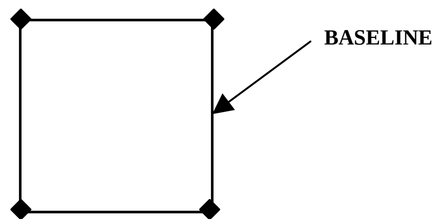


Single Baseline	Leveling Costs	GPS Costs	GPS Savings
1 Km	$680	$1,620	-138%
2 Km	$1,360	$1,620	-19%
3 Km	$2,040	$1,620	21%
4 Km	$2,720	$1,620	40%
5 Km	$3,400	$1,620	52%
10 Km	$6,800	$1,620	76%

Comparative Costs for Single Baselines

The second table shows cost comparisons for expanding a survey network, based on a four-point box, one box at a time. This example is consistent with how the National Height System would be implemented at the recommended 10-kilometer spacing. Note that using GPS methods result in almost a 90 percent cost savings over conventional surveying methods.

For an expanding network with four new points at a time forming multiple baselines, with each baseline length between 1 and 10 kilometers, the comparative costs between leveling and GPS are shown below:



4-POINT BOX

Single Baseline Length	Total Leveling Length	Leveling Costs	GPS Costs	GPS Savings
1 Km	4 Km	$2,720	$3,240	-19%
2 Km	8 Km	$5,440	$3,240	40%
3 Km	12 Km	$8,160	$3,240	60%
4 Km	16 Km	$10,880	$3,240	70%
5 Km	20 Km	$13,600	$3,240	76%
10 Km	40 Km	$27,200	$3,240	88%

Comparative Costs for Multiple (Network) Baselines

Major Findings of the Study

Five major findings were identified from the user forums.

1. The Nation needs a reliable and efficient means to determine "absolute" heights. This can best be accomplished through the use of GPS technology in conjunction with NGS technical guidelines and an accessible National Height System.

2. The Nation needs a reliable, cost-effective, standardized, legally established national vertical reference datum (NAVD 88) and the infrastructure (NHS) through which to access and utilize it.

3. The Nation needs high accuracy digital elevation models based on NAVD 88 as supported by the National Height System.

4. The Nation needs a nationwide differential GPS system to support accurate real-time three-dimensional applications.

5. The Nation needs cost-effective elevation surveys of floodplains and coastal areas vulnerable to flooding that are based on NAVD 88. GPS is the best technology to accomplish this.

Study Recommendations

The study clearly identified the need for a National Height System (NHS) and that GPS technology, conducted in accordance with NGS guidelines, is the most cost-effective method to implement it.

This study provides recommendations on how to best accomplish this and satisfy the first two Major Findings, as described below. The last three Major Findings are in the process of being implemented by other Federal agencies and their partners, but would be greatly enhanced by an accessible NHS.

The study recommends a two-phase approach to modernize and sustain NHS throughout the conterminous United States. Phase 1, described in detail in the report, would focus on the survey and scientific work needed to establish the basic framework of NHS, while Phase 2, addressed in the report but in less detail, would ensure the system's continued sustainability.

Phase 1 - Establish the System's Framework

Phase 1 would involve a cooperative effort among the private sector and Federal and state agencies to establish NHS' basic framework of reference survey points, a network of 55,000 bench marks with 10 km by 10 km nominal spacing called the Federal Base System, with their heights accurately determined by GPS. Phase 1 would be accomplished over a 5-year span, utilizing a state-by-state approach.

The first step of Phase 1 would be to conduct two prime demonstration projects in California and North Carolina during the first year. These states are subject to extreme seismic activity, subsidence, riverine and coastal flooding, coastal erosion, and accelerating development. They are ideal for fully refining the GPS techniques and guidelines needed to most effectively implement NHS, and conduct the training and transference of this technical expertise to the state and private partners needed to develop the large institutional capacity required to implement NHS on a national basis. This expanded, constantly growing technical capacity will, as the next step, enable NHS to be implemented in a larger number of states each year as the next step.

During all steps of Phase 1, the private sector would perform the geodetic survey projects under NGS oversight and technical guidelines. The private sector projects are the most resource intensive aspect of the activities needed to establish the framework. In general, these projects consist of activities such as:

- identifying existing, or establishing new, survey points suitable for incorporation into NHS;
- collecting, processing, and adjusting GPS and leveling data connecting these survey points into NHS;
- preparing appropriate documents and reports; and
- submitting results to NGS for quality control and assimilation into NHS.

NGS oversight and documentation responsibilities would include the following:

- managing the implementation effort, determining priority areas, selecting qualified private-sector contractors, managing contracts, and providing technical supervision;
- analyzing, documenting, and publishing the accuracy of the GPS-derived heights and accuracies obtained by the projects; and
- performing technology transfer activities to promote understanding and implementation of the National Height System including: publishing documents, conducting seminars and workshops, and developing training seminars for technical personnel to become instructors.

The following tables estimate and compare the costs of using conventional surveying methods versus GPS technologies to complete Phase 1 of the National Height System modernization. The higher costs shown for conventional surveying techniques are the direct result of the significantly higher time and labor demands. It should be noted that this study only estimates the overall costs to implement the National Height System and makes no statement or implication about the source(s) of these funds.

Activity	Estimated Cost of Using Conventional Surveying Technologies		Estimated Cost of Using GPS Technologies	
State	**California**	**North Carolina**	**California**	**North Carolina**
Subtotal	**$41,200,000**	**$20,040,000**	**$4,600,000**	**$2,380,000**
TOTAL	**$61,240,000**		**$6,980,000**	

Comparative Costs of Implementing Phase 1 NHS Demonstration Projects During the First Year

Activity	Estimated Costs of Using Conventional Surveying Technologies	Estimated Costs of Using GPS Technologies
TOTAL	$596,000,000	$66,000,000

Comparative Costs of Implementing the National Height System over 5 years

Phase 2 - Ensure the System's Sustainability

The need for Phase 2 was addressed in the full report, but was not fleshed out in great detail. State, local, and private sector partners would be responsible for maintaining NHS, and potentially expanding it into urban or other areas requiring a denser network for greater accessibility. This would be similar to the systems in place to maintain the horizontal component of NSRS. The study participants agreed that maintaining the system's sustainability would necessitate NGS' continued provision of technical leadership, program oversight, and security.

1 -- STUDY BACKGROUND

1.1 Introduction

This report was prepared in response to the direction contained in House Report 105-207 (to accompany H.R. 2267 – Departments of Commerce, Justice, and State, the Judiciary, and Related Agencies Appropriations Bill, Fiscal Year 1998) that the National Geodetic Survey (NGS) "conduct a National Height Modernization Study to demonstrate the effectiveness of this work in California and in western North Carolina. The Committee expects the NGS to conduct this study in consultation with state and local governments and the private sector." The results of the study not only present a compelling argument for the need to modernize the National Height System (NHS) – the vertical component of the National Spatial Reference System (NSRS) -- but also show how to use the Global Positioning System (GPS) to accomplish height modernization with tremendous cost savings. GPS and Differential GPS (DGPS), both vital to height modernization, are explained in detail in sections 8.6 and 8.7 of the Appendix.

1.2 Definitions

Heights vs. Elevations. Throughout the report, the terms "height" and "elevation" are used interchangeably and generically to avoid confusion caused by the use of precisely-defined technical terms, e.g., orthometric heights, ellipsoid heights, dynamic heights, and geoid heights.

National Spatial Reference System (NSRS). The NSRS is that portion of the National Spatial Data Infrastructure (NSDI) that provides accuracy to 2- or 3-dimensional geospatial data. In many respects, the NSRS is the foundation of the NSDI, both of which are explained in detail in sections 8.1 and 8.2 of the Appendix.

<u>National Height System (NHS)</u>. The NHS is the vertical component of the NSRS, i.e., that portion of the NSRS that determines elevations and elevation accuracies.

For centuries, America's height systems have relied upon traditional leveling, also known as differential leveling or conventional leveling. Leveling is based on a series of line-of-sight measurements of elevation differences, measured inland from surveyed benchmarks with elevations referenced to mean sea level (msl). The National Geodetic Vertical Datum of 1929 (NGVD 29), for example, assumed that 21 tidal stations in the United States represented the same (zero) elevation above msl. However, modern surveys prove that msl in Boston, for example, is a different elevation than msl at other tidal stations along the Atlantic, Gulf, and Pacific coasts. This is one of numerous technical reasons why NGVD 29 elevations need to be corrected by offsets, varying up to five feet, for conversion to NAVD 88 elevations.

Leveling in this report is synonymous with conventional, traditional, or differential leveling performed by surveyors who first "level" their optical survey instruments to obtain line-of-sight perpendicular to the local direction of gravity. Precise or geodetic leveling refers to the more accurate forms of leveling. Such surveys are primarily dependent on the rules of gravity.

GPS surveys in this report are usually synonymous with GPS vertical, height, or elevation surveys, GPS 3-D positioning, or GPS leveling. GPS surveys are essentially independent of the local direction of gravity and do not require line of sight between points surveyed. GPS horizontal surveys are described as such, or as GPS 2-D surveys. GPS surveys are primarily dependent on the rules of geometry.

Leveling uses optical survey instruments that have been "leveled" relative to the local direction of gravity. However, the local direction of gravity varies as a result of mass excesses or deficiencies in the earth, causing the geoid (the equipotential surface with gravity equal to that at msl) to undulate up and down at variable distances above or below the reference *ellipsoid.* The reference ellipsoid is used for determination of horizontal and vertical coordinates of points on or near the earth's surface.

Elevations derived from leveling have accuracies *relative* to numerous factors explained in the Appendix, whereas elevations derived from GPS vertical surveys can essentially have *absolute* accuracy, relative only to the earth's center. The accuracy of elevations from leveling is typically specified in relative terms, e.g., 0.4-mm times the square root of the length of the level loop surveyed (in kilometers). Alternatively, the accuracy of elevations from GPS surveys are typically specified in absolute terms, e.g., ±2-cm at the 95% confidence level.

The *modernized NHS* corrects major deficiencies of the past and permits elevations to be determined with accuracies that approach "absolute." The modernized NHS consists of the following:

- **3-D CORS Stations (zero errors)** comprise a nationwide network of hundreds of 3-D Continuously Operating Reference Stations (CORS) surveyed by NGS or other Federal or state agencies (using NGS' most rigorous specifications). With continuous, ongoing surveys, relative to the full constellation of GPS satellites, CORS stations are surveyed so well that their elevations are assumed to have zero errors relative to the center of the earth. Although all surveys are relative, elevation surveys relative to CORS approach the pure definition of *absolute accuracy*. Some CORS stations provide data for high accuracy GPS post-processing of elevation data, while other CORS stations are radio beacon sites that instantaneously transmit differential GPS corrections for users with GPS real-time kinematic (RTK) applications. See the Appendix for additional details.

- **3-D HARN Stations** comprise a network of thousands of 3-D High Accuracy Reference Network (HARN) stations surveyed by NGS or other Federal or state agencies. These are well-documented, permanent survey monuments that are available for public use for either GPS or traditional elevation surveys.

- **"Blue Booked" survey monuments** comprise a network of hundreds of thousands of 2-D and 3-D survey monuments that have been surveyed over the years and maintained by NGS in the NSRS. Survey Data Sheets for each survey monument are easily available to the public on CD-ROM or via the Internet. When used as a noun, *blue book* refers to a 3-volume set of publications (with blue covers) entitled: "Input Formats and Specifications of the National Geodetic Survey Data Base." It is a user's guide for preparing and submitting geodetic data for incorporation into NGS' data base. Survey data that are entered into NGS' data base become part of the NSRS. The guide comprises three volumes: volume I covers horizontal geodetic data, volume II covers vertical geodetic data, and volume III covers gravity data. When used as a verb, *blue booking* refers to the process of submitting survey data to NGS consistent with rigorous *blue book* procedures for preparing and submitting geodetic data for use by others.

- **The Geoid Model** (currently Geoid 96) is NGS' mathematical model that provides the geoid height, i.e., the distance of the geoid above or below the ellipsoid. For any given latitude and longitude, the geoid height is necessary for conversion between orthometric heights (from leveling) and ellipsoid heights (from GPS).

- **The Vertical Datum** is the basis of reference for all elevation surveys. Vertical datums are explained in detail in the Appendix. The North American Datum of 1983 (NAD 83) replaced the North American Datum of 1927 (NAD 27) years ago as the modernized horizontal datum within the NSRS. However, the North American Vertical Datum of 1988 (NAVD 88) has never been implemented nationwide as the modernized replacement for the National Geodetic Vertical Datum of 1929 (NGVD 29) in spite of its official designation by the Federal Geodetic Control Subcommittee (FGCS) of the Federal Geographic Data Committee (FGDC) in 1993.[1]

Digital Elevation Models (DEMs) are digital files of ground points for which latitudes, longitudes, and heights are known. According to the American Society for Photogrammetry and Remote Sensing (ASPRS)[2], DEMs are uniformly spaced points (grid or lattice) such as USGS DEMs with standard point spacing of 30m x 30m or 100m x 100m. But the term "DEM" is also used in a generic sense to include digital elevation data that are non-uniformly spaced, such as Digital Terrain Model (DTM) and Triangulated Irregular Network (TIN) data produced by a variety of means. DEMs are often used as

[1] Federal Register Notice, Vol. 58, No. 12, June 24, 1993, designated NAVD 88 as the official replacement of the older NGVD 29 vertical datum

[2] Maune, David, 1996, "Introduction to Digital Elevation Models (DEM**), *Digital Photogrammetry, An Addendum to the Manual of Photogrammetry***, American Society for Photogrammetry and Remote Sensing (ASPRS), pp. 131-134.

the base for topographic and hydrographic mapping and as the height component of Geographic Information Systems (GIS).

1.3 Need for the Study

NAVD 88 is an elevation reference system designed to be integrated into a seamless network of horizontal and vertical reference points, gravity data, GPS satellites, and tracking stations. It supports such diversified uses as:

- Precise navigation and aircraft landing systems
- Floodplain management and the National Flood Insurance Program
- Highway and railroad infrastructure systems
- Intelligent vehicle highway systems
- Earthquake, volcanic, and subsidence research programs
- Disaster preparedness and relief efforts
- Water transportation infrastructure
- Precision agriculture

The change from NGVD 29 to NAVD 88 was necessary to provide for three-dimensional positioning on a global level, such as is afforded by GPS, and to remove distortions in the older vertical datum as described by Zilkoski et. al.[3]. In the conterminous United States, the height differences between NGVD 29 and NAVD 88 vary between –40-cm (-16 inches) and +150-cm (+59 inches).

Implementation of NAVD 88 means developing the network through recompilation of existing data and execution of new surveys and studies to bring the horizontal, vertical, and gravity control networks together into a unified system, joined and maintained by GPS. NGS conducts such surveys under the authority of 33 U.S.C. 883a et seq. and the Office of Management and Budget (OMB) Circular A-16 (Oct. 19, 1990).

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[3] Zilkoski, David B., Richards, John H., and Young, Gary M., 1992, "Results of the General Adjustment of the North American Vertical Datum of 1988," ***Surveying and Land Information Systems,*** Vol. 52, No. 3, pp. 132-137.

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1.4 Study Goals

The goals of the National Height Modernization Study are to:

- Identify and document user requirements for height data, including those requirements utilizing both vertical and horizontal data.
- Identify and document major users and applications of the National Height System and GPS-derived height data.
- Identify and recommend the best, most cost-effective actions that meet the documented user requirements, taking into consideration all technologies available.
- Evaluate the estimated costs to implement the recommended actions, and their benefits to the nation.

1.5 Study Approach

The study included the following:

- User forums held in California and North Carolina to determine who the elevation "users" and "providers" are; to determine user needs assessments by application categories; and to define the role of NGS in satisfying those requirements
- Evaluation of technological opportunities to satisfy these needs
- Compilation of GPS case study "lessons learned" from leading survey firms knowledgeable with regard to NGVD 29 and NAVD 88
- Cost comparisons between GPS and leveling from controlled test surveys
- Analysis of options and development of conclusions and recommendations

The results are a comprehensive analysis of elevation needs, and technical proposals for satisfying those needs, whether provided by NGS or others.

2 -- USER FORUMS

2.1 Background

This chapter summarizes the results of user forums, sponsored by NGS in Ontario, California, and Raleigh, North Carolina on January 26-27, 1998 and February 4-5, 1998, respectively. The purpose was to provide information regarding the study and to obtain insights and suggestions from individuals in the community of spatial data users, including surveyors, engineers, mappers, shippers, and marine pilots, for contribution to the study and aid in evaluating the technical, financial, legal, and economic aspects of modernizing National Height System technology.

The forum participants represented a wide range of spatial data user communities. The forum format included an overview by NGS of the current efforts, and panels of GPS advocates whose objective was to challenge participants and provoke thinking about the potential for modernizing the National Height System. The participants provided their individual feedback and recommendations on the following:

- Existing unmet user requirements
- Potential applications of GPS
- An indication of priorities and the proposed Federal role in meeting unmet requirements.

The following sections are a synthesis of the inputs from the two user forums.

2.2 Unmet Needs or Requirements

In an introductory 'brainstorm" session, the interactive discussion groups presented a wide range of unmet needs and requirements for height data. The most common themes reflected needs for the following:

- North American Vertical Datum of 1988 (NAVD 88) densification and improvement
- Relating existing vertical datums, including tidal datums, to one another
- An improved geoid model, necessary for adjusting GPS-derived ellipsoid heights to leveling-derived orthometric heights
- Continuously Operating Reference Station (CORS) densification and improvement
- National standards and guidelines for GPS-derived orthometric heights
- Improvements to the National Spatial Reference System (NSRS)
- Infrastructure for real-time 3-D positioning with GPS

2.3 Potential GPS Applications in Height Modernization

Subsequently, the interactive groups discussed additional GPS applications in height modernization not offered by panelists or NGS. These ranged from using GPS for mapping, navigation, safety, and scientific applications, to using it for land-based private and commercial activities such as ski resort and golf course facilities management, fishing, agriculture, land fill height monitoring, forestry, and snow plow management. Major GPS application themes that frequently arose from various participants included:

- Land Transportation and Safety: real-time positioning of vehicles; transportation of cars, trains, trucks, buses, emergency vehicles, and heavy equipment; management of traffic congestion
- Marine Navigation and Safety: controlled dredging and hydrographic surveys; provision of accurate, real-time information on under-keel clearance; collision and grounding avoidance; improvements in shipping cost-effectiveness
- Air Navigation and Safety: avoidance of mid-air collisions and controlled flight into terrain (CFT); zero-visibility landings; flight simulations; airport and airspace elevations and obstructions; security
- Infrastructure Management: modeling and monitoring the nation's infrastructure; monitoring of subsidence and crustal motion, ground

and subsurface water levels; hydrologic and hydraulic modeling; 3-D location of utilities – above/below ground; mining and construction.

- Precision Farming: water delivery and irrigation control; drainage; fertilizer/pesticide delivery and application; monitoring plant growths and yields; vegetation and turf management; erosion and sedimentation modeling, assessment, and management; and mitigation of non-point source pollution.

- Environmental Protection: environmental assessments; effects of ocean rise; hazardous incident monitoring; natural resource management

- Flood Mitigation: proactive floodplain management, flood hazards and risk assessments, floodproofing initiatives, strengthening the National Flood Insurance Program (NFIP)

- Public Safety: Hazard monitoring (seismic and dam deformation); emergency response; snow removal management

2.4 Highest Priority Potential Applications

Next, the user forum participants focused on applications believed to have the highest potential for GPS. The themes most frequently named as highest potential were:

(1) Need for vertical accuracy and consistency among GIS databases, especially as used for:

- Floodplain management and hazard mitigation
- Public works/infrastructure management
- Subsidence/crustal motion monitoring

(2) Need for real-time GPS applications, especially for the following:

- Air and marine navigation
- Land-based vehicles, including construction equipment
- Precision agriculture
- Emergency response

2.5 Federal Role in National Height Modernization

Finally, the user forum groups provided feedback on the Federal role in National Height Modernization. The participants described the desired Federal role as follows:

(1) In setting specifications, guidelines, and/or standards for elevation surveys and data, NGS' role should be:

- Developing guidelines for use of GPS technology to achieve desired accuracy.
- Developing programs for adoption by state, regional, and local governments to manage geodetic control issues, and establish a uniform format for exchange among geodetic or GIS software and hardware vendors.
- Being more involved in influencing international standards, specifications, and guidelines.

(2) In establishing strong national leadership, NGS' role should include:

- Coordination of the evolution and nationwide implementation of the modernized National Height System (NHS)
- Continued research in new technology (in-house and through grants)
- Work with GPS manufacturers for standardization of GPS data

Specifications or Guidelines?

There is no significant difference in content between specifications and guidelines. They each outline a set of steps or procedures that result in the achievement of specific goals or standards. The difference is in their perceived level of authority. Specifications are seen as rigid, while guidelines are more flexible, a set of procedures recommended for reaching a specific goal, but recognizing that they are not necessarily the only path to that goal. In the case of a national height standard, GPS techniques can be used in attaining a certain level of positioning accuracy.

- Serving as a catalyst to establish the number of base stations necessary for 1 cm accuracy, the highest accuracy requirement specified by the users
- Exploring alternative reference systems, e.g., the International Earth Rotation Service Terrestrial Reference Frame (ITRF)
- Ensuring that all projects using Federal funds are "blue booked" for inclusion in the National Spatial Reference System (NSRS)
- Transferring new technology

(3) For maintaining the database at a Cooperative Base Network (CBN) level, NGS' role should include:

- Establishing and maintaining the physical framework
- Working with partners at the local level to maintain the network
- Maximizing the use of local surveyors to accomplish surveys
- Maintaining and distributing data; reviewing and ensuring the quality of NSRS
- Enhancing existing orthometric height system standards around NAVD 88
- Coordinating and overseeing orthometric heights on High Accuracy Reference Network (HARN) stations and tidal and lake bench marks
- Developing and distributing an improved geoid model, and maintaining the capability to establish the highest order survey network
- Coordinating expansion of CORS and beacon stations to centimeter accuracy nationwide

(4) For verifying the consistency of data, NGS' Federal role should include documenting data quality and metadata, and coordinating data distribution by others.

(5) For working with the user community, NGS' role should include:

- Strengthening the role of the State Geodetic Advisors
- Transferring new technology and sponsoring trainer training
- Enhancing educational outreach through new technology, e.g., Internet, video conferencing

- Increasing staff capabilities to test and evaluate new equipment
- Providing reports to users
- Ensuring the use of user friendly software for NSRS data
- Providing easy access data retrieval, e.g., via the Internet

(6) Serving as a data and information clearinghouse for the NSRS.

(7) Advocating and serving as the key GPS interface with the American Congress on Surveying and Mapping (ACSM), the American Society for Photogrammetry and Remote Sensing (ASPRS), the Urban and Regional Information Systems Association (URISA), etc.

2.6 Major Messages from the User Forums

There was a high level of support for modernizing the NHS. Participants particularly highlighted key roles for GPS in land, air, and marine transportation; infrastructure management; agriculture; flood mitigation; and emergency management.

Consistent with the responsibilities of the Federal Geographic Data Committee (FGDC), shown in Figure 1, and the Federal Geodetic Control Subcommittee (FGCS), shown in Figure 2, the Federal role in future use of GPS for height modernization was supported. This included greater Federal investment and coordination with one agency in the lead role for GPS development and application; the need for the U.S. to maintain world leadership in GPS standards and promote national and international consistency; and reduced dependency on leveling.

Unmet needs focused on:

(1) Standards and guidelines for GPS surveys

(2) Conversion/updating from NGVD 29 to NAVD 88

(3) Increased densification of vertical control

(4) Centralized source of GPS information

(5) Improved data system distribution

(6) An improved geoid model

(7) Combining of traditional and GPS leveling

(8) Infrastructure to support real-time 3-D positioning.

Highlights of comments regarding users and partners included the ideas that future use of GPS for heights requires more training for use of NAVD 88 and GPS and the desirability of enhanced partnering between NGS, DOD, DOT, and the private sector in GPS use.

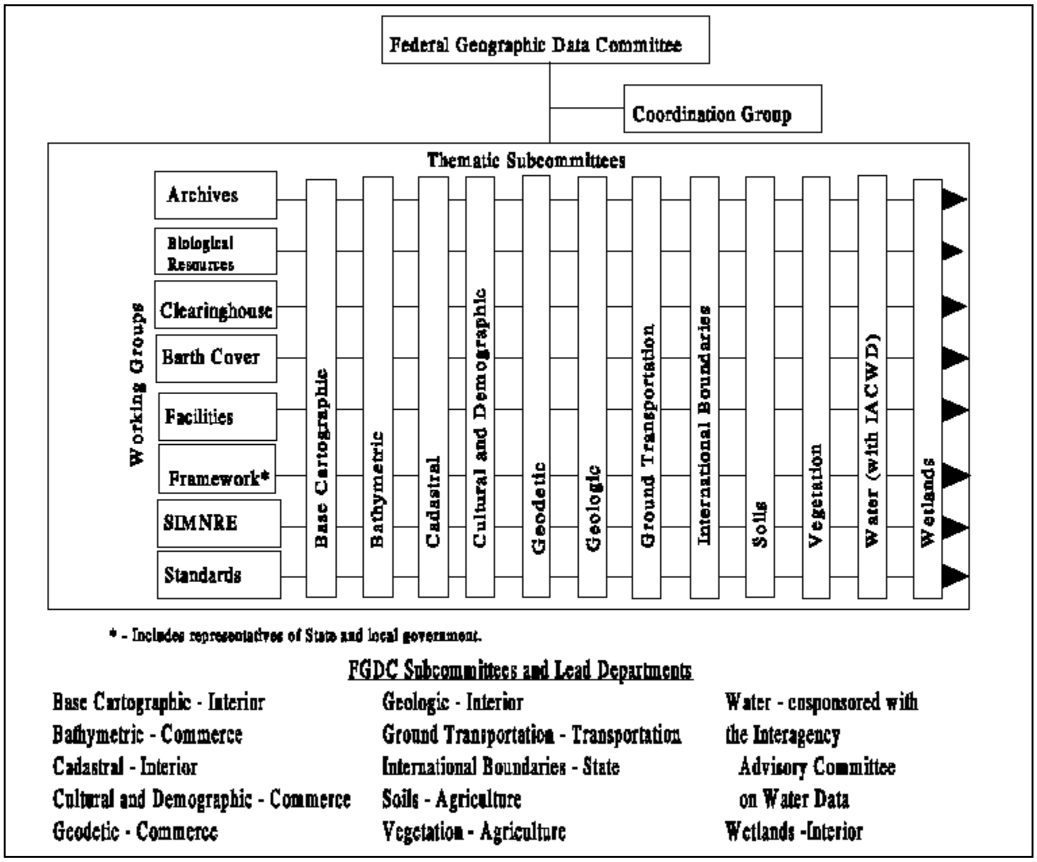

Figure 1 Federal Geographic Data Committee (FGDC) Structure

The FGDC is chaired by USGS

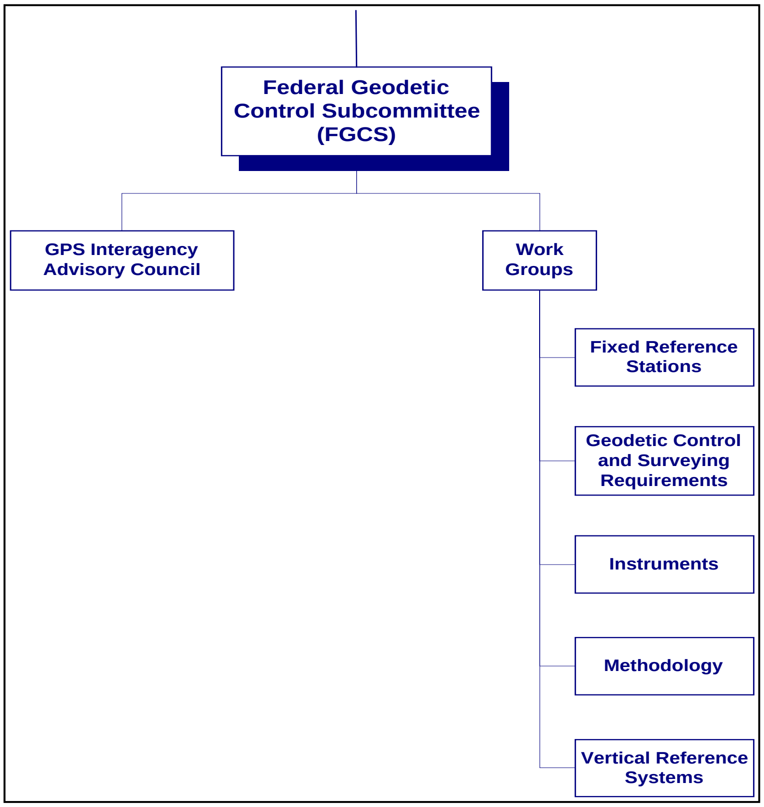

Figure 2 The Federal Geodetic Control Subcommittee (FGCS) Structure. The FGCS is chaired by NGS

The GPS Interagency Advisory Council (GIAC), chaired by NGS, represents non-navigation aspects of GPS for all civil federal requirements.

3 -- USER NEED ASSESSMENTS

3.1 Application Categories

Nineteen user application categories defined the major, but not total users of elevation data. These 19 applications were grouped in five summary categories as follows:

What do these five functions all have in common?

They all need improved Digital Elevation Models (DEM) and improved 3-D positioning of fixed and moving objects; and implementation of NAVD 88 is critical!

1. **Public Safety**
2. **Transportation Management**
3. **Infrastructure Management**
4. **Construction and Mining**
5. **Agriculture and Natural Resources**

In each of these five summary categories, Tables 1 through 5 summarize the individual application category elevation requirements in three forms: (1) Digital Elevation Models (DEMs), (2) static elevations of fixed features, and (3) real-time kinematic (RTK) elevations of moving objects. In one application (police, E-911, and fleet vehicle tracking), the users require horizontal real-time positioning only; but this report will show that these 2-D positioning requirements would also be satisfied as a result of GPS solutions for other applications that require 3-D RTK positioning.

3.2 Public Safety

"Public Safety" is herein defined to include police, E-911, and fleet vehicle positioning; disaster preparedness and response; flood mitigation; coastal stewardship; and seismic monitoring. Elevation requirements for these applications are summarized in Table 1.

Elevation Requirements by Application:	DEM Vertical Accuracy	Static Elevations	RTK Elevations
Police, E-911, Fleet Vehicles	**N/A**	**N/A**	**Horiz. only**
Disaster Prep. & Response	**1 m**	**5 cm**	**15 cm**
Flood Mitigation	**15 cm**	**5 cm**	**15 cm**
Coastal Stewardship	**15 cm**	**5 cm**	**15 cm**
Seismic Monitoring	**1 m**	**1 cm**	**1 cm**

Table 1. Elevation Requirements for Public Safety Applications

Digital Elevation Models (DEMs), with vertical accuracy of 15 cm (6 inches), are vital to the Federal Emergency Management Agency (FEMA) for proactive floodplain management and coastal monitoring and protection. Real-time kinematic (RTK) GPS elevation surveys are also critical for these FEMA requirements. Continuous GPS monitoring, with alarms that are sounded when movement exceeds specified thresholds, satisfies the 1-cm RTK requirements.

3.2.1 Police, E-911 and Fleet Vehicle Services

Although requirements are primarily for horizontal positioning, differential GPS (DGPS) is vital for police, fire departments, ambulances, buses, taxis, delivery trucks, and other fleet vehicle applications. Nationwide DGPS (NDGPS), described in Section 8.8 of this report, is superior because real-time differential corrections would be available nationwide without individual communities needing to establish and operate their own local GPS reference station and transmitter. NDGPS, used with Automated Vehicle Location (AVL) and Computer Aided Dispatch (CAD), enable vehicle dispatchers to quickly identify available assets closest to an emergency.

With DGPS (and more efficiently with NDGPS), E-911 dispatchers know where emergency vehicles are currently located, and the fastest way to respond to an emergency. When a police officer, for example, needs rapid reinforcements, the push of a "send help fast" button on the dashboard would accurately inform the dispatcher where help is needed, without delays for radio communication and verbal directions to the scene. This can be done today without DGPS or NDGPS, but GPS autonomous positioning has errors of 100 meters; such errors could cause police reinforcements to be sent to the wrong block. With NDGPS, the AVL would identify the correct street and the accurate location on that street.

The U.S. Department of Transportation (USDOT)[4] estimated benefits of over $8 billion, over the projected 15-year life of NDGPS, for public safety alone. The National Transportation Safety Board (NTSB) considers NDGPS to be an essential technology for saving lives.

3.2.2 Disaster Preparedness and Response

The Federal Emergency Management Agency (FEMA) has embarked on a full-scale effort to help build safer communities. FEMA's goals include increasing public awareness of hazards and loss reduction (mitigation) measures, reducing the risk of loss of life and property, and protecting our nation's communities and the economy from all types of natural and technological hazards.

Three FEMA reports are referenced herein. The first FEMA report indicates that the overall costs of disasters to the United States has grown significantly over the last decade; the average annual losses have increased to $13 billion. The good news, however, is that *mitigation works*, and many things can be done to reduce the impact of future disasters. For example, one FEMA report indicates: "During Hurricane Opal (Florida, 1995), none of the 576 major habitable structures located seaward of the Coastal Construction Control Line (CCCL) and permitted by the State under current standards sustained substantial damage. By contrast, 768 of the 1,366 pre-existing major habitable structures seaward of the CCCL sustained substantial damage."[5]

A second FEMA report[6] identifies and assesses risks for various types of natural and technological hazards. Many of those risks, especially flood, coastal erosion, and hurricane tidal surges, are elevation based. Thus, improved elevation data leads to improved risk mitigation.

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[4] U.S. Department of Transportation, March 24, 1998, ***Nationwide Differential GPS Report****;* Washington, DC, p. 64

[5] Federal Emergency Management Agency, March 1997***, Report on Costs and Benefits of Natural Hazard Mitigation,*** Washington, DC, pp. 1 and 33.

[6] Federal Emergency Management Agency, 1997, ***MULTI HAZARD, Identification and Risk Assessment, A Cornerstone of the National Mitigation Strategy****,* Washington, DC, p. i.

For floods and hurricanes, 3-D DGPS techniques are routinely used to survey the heights of buildings, high water marks, and tidal surge limits. FEMA often produces GPS Elevation Certificates of buildings damaged by floods and tidal surges because such damages are not covered by conventional homeowners' insurance policies. By eliminating requirements for local DGPS base stations for pre- and post-disaster surveys, an NDGPS capability could reduce the cost of such damage surveys by approximately one-third, saving FEMA several hundred thousand dollars annually in survey costs.

Disaster preparedness and response also needs horizontal data that would be provided most cost-effectively by NDGPS. NDGPS is vital to Federal, state, and local emergency response personnel, because earthquakes, hurricanes, and tornadoes often destroy street signs, and street addresses are very difficult to determine. Hurricane Andrew, for example, destroyed every street sign for miles in all directions, making it extremely difficult for relief workers to identify locations. In rural areas, houses may have no street addresses at all, but rely on post office boxes of rural route systems for mail delivery. Without street names or addresses, GPS coordinates become the addressing scheme of choice, especially for FEMA and Disaster Field Offices, which utilize Geographic Information System (GIS) technology.

3.2.3 Flood Mitigation

Relevant Facts

According to the same (second) FEMA study[7], "over 9,000,000 households and $390 billion in property are at risk from flooding" and property damage, excluding agricultural losses, has escalated to roughly $2.15 billion per year, mostly uninsured. As of January 1998, there were only 3.9 million flood insurance policies in effect. Accurate elevation

According to a third FEMA report[8], only one-third to one-half of U.S. floodplains are studied by *detailed* methods which compute base flood

[7] Ibid., p. 136

[8] Federal Emergency Management Agency, November 1997***, Modernizing FEMA's Flood Hazard Mapping Program, A Progress Repor****t*, Washington, DC, pp. 11 and 19

elevations (BFEs). Instead; over half use *approximate* methods in which BFEs are not computed. Furthermore, over 2,700 floodprone communities are unstudied.

Because of the unavailability of accurate and affordable elevation data, the National Flood Insurance Program (NFIP) currently relies on horizontal criteria for flood risk determinations; and the NFIP has been unable to perform detailed flood studies for over half of the floodplains in the U.S.

With high-accuracy DEMs and GPS elevation surveys, explained below, FEMA can:

(1) Establish combined horizontal/vertical criteria for high-accuracy flood risk determinations

(2) Automate the hydrologic and hydraulic (H&H) analyses needed to rapidly and cost-effectively produce accurate and complete flood hazard information for the entire nation

(3) Cost effectively support implementation of FEMA's Flood Hazard Mapping Modernization Plan

(4) Yield the full benefits of *proactive floodplain management*.

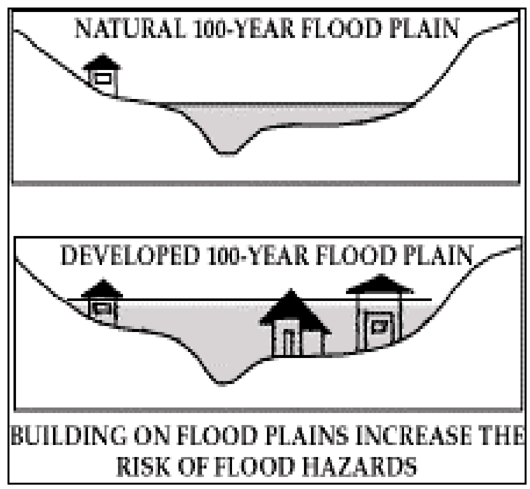

Figure 3 Increased Risk Due to Land Development in Flood Plains

Discussion

As stated above, the NFIP has not had the support needed to perform detailed flood studies for many of the flood-prone communities in the U.S. and lacks accurate elevation data. Furthermore, many communities choose not to participate in the NFIP because they do not want to adopt floodplain management measures required by the NFIP. In such communities, owners of flood-prone buildings cannot purchase flood insurance.

With high-resolution, high-accuracy DEMs produced by the new LIDAR (LIght Detection And Ranging) and/or IFSAR (Interferometric Synthetic Aperture Radar) technologies, discussed in the Appendix of this report, legitimate flood risks could be accurately determined. Furthermore, automated hydrologic and hydraulic (H&H) analyses could be used to rapidly and cost-effectively produce accurate and complete flood hazard information for the nation. Consequently, flood insurance studies could be rapidly and efficiently updated as conditions change.

Figure 4. Two Houses in St. Charles County, Missouri During the Flood of '93. Photos provided as a courtesy by the St. Louis Post-Dispatch.

With flood insurance, an elevation difference of one foot can mean the difference between $1,160 and $450 in annual premiums for $100,000 coverage.[9]

By performing high-accuracy GPS surveys of all buildings in or near Special Flood Hazard Areas (SFHAs), lowest floor elevations are compared with base flood elevations (BFEs) for that location, from FEMA's Flood Insurance Rate Maps (FIRMs), to determine the estimated depth of interior flooding from the 100-year (1% annual chance) flood. Combined with the pre-flood replacement value of the

[9] Federal Insurance Administration, ***Flood Insurance Manual,*** 1994 Edition, Revised October 1, 1997, p. "Rate 4."

building and the area of the building's "footprint," ***flood damage models can accurately predict future flood damages, not just for one building, but for every building in or near a community's SFHA.***

Proactive Floodplain Management

Knowing the inevitable damages that will result from future flooding, communities with comprehensive elevation data can proactively:

(1) Convince owners of their true need for flood insurance, based on legitimate (elevation-based) flood risk determinations

(2) Identify candidate buildings for retrofitting/floodproofing prior to actual floods, rather than wait for post-flood mitigation steps to force this action

(3) Use the predicted flood damages to determine where it is cost-justified to initiate drainage improvement projects that will lower the BFEs for an area

(4) Determine depths of interior flooding and estimate flood damages – rapidly -- when floods actually occur, without needing time-consuming post-flood surveys of individual buildings.

With pre-surveyed elevation data for buildings, flooded communities would merely survey the high water marks at a few key locations in town, model the flood water elevations, and compute the actual depth of interior flooding for each building. With actual depths of interior flooding and previously known replacement value and building "footprint" area, it takes very little time to accurately estimate the flood damages to every building in the community in order to expedite funding assistance to those who qualify.

Conclusions

The current procedure (SFHAs) used by lending institutions for horizontal flood risk determinations, which causes 15,000,000 buyers annually[10] to pay $25 or more for "in/out" map determination, has inherent limitations that cannot be corrected without the addition of

[10] Federal Emergency Management Agency, November 1997, ***Modernizing FEMA's Flood Hazard Mapping Program, A Progress Report***, Washington, DC, p. v.

vertical criteria for flood risk determinations. Eliminating the need for each home-buyer to pay for horizontal "map determinations" of flood risk would save these taxpayers (albeit not the Federal government) $375 million annually, or $5.6 billion over a 15-year period used to document the life-cycle benefits of NDGPS and other initiatives discusses in this report. Furthermore, the results of using vertical criteria for flood risk determinations would be vastly superior.

3.2.4 Coastal Stewardship

According to a FEMA study[11] that relied on study data from the U.S. Army Corps of Engineers, approximately 20,500 miles (33,000 km) of the 84,240 miles (132,350 km) of U.S. shoreline experience “significant” erosion, while 2,700 miles (4,350 km) are subject to “critical” erosion. There are 260 coastal counties in the U.S. FEMA inventoried 26 of these counties (10%) in 1997, including GPS elevation surveys of 45,000 buildings within coastal high hazard zones (V-zones, subject to velocity wave action). Thousands of buildings are vulnerable to coastal erosion and/or velocity wave action from hurricane tidal surges. If other coastal counties are similar, then 450,000 buildings nationwide could be in V-zones. Projected erosion rates along the Gulf and Atlantic coasts are typically two feet per year, and one foot per year on the Pacific Coast. FEMA needs elevation surveys of all buildings in V-zones for multi-hazard mitigation

In addition to coastal erosion, coastal communities are also impacted by a projected rise in sea level as a result of global warming. According to the Environmental Protection Agency (EPA)[12], this rise could be as high as 1-meter during the next century. When the White House asked EPA for statistics on the numbers of buildings to be impacted by the predicted sea level rise, EPA first attempted to use USGS DEMs with 30-meter point spacing and 7-meter root mean square errors. Next, EPA used USGS 7.5-minute quadrangle maps with 10-, 20-, and 40-foot contour intervals. Both methods were unacceptable, and nothing better was

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[11] Federal Emergency Management Agency, 1997 ***MULTI HAZARD, Identification and Risk Assessment, A Cornerstone of the National Mitigation Strategy***, Washington, DC, p. 160.

[12] U.S. Environmental Protection Agency, 1997 ***Global Warming, The Probability of Sea Level Rise***, EPA Report No. 230-R-95-008, Washington, DC.

available. The White House was informed that no good estimates could be provided in answer to the question.

Florida is considering the annual or seasonal funding of LIDAR-generated DEMs of all Florida coastlines in order to monitor coastal erosion that endangers life and property; evaluate changes to beaches, sand dunes, and barrier islands that protect coastal resources; and improve the accuracy of erosion rates and projected erosion hazard areas within which new development needs to be controlled. The footprints and heights of beachfront buildings would be documented, providing information that has a variety of uses, including planning for new developments[13] The entire United States needs such DEMs, not just for coastal protection but also for the variety of other applications discussed in this report.

3.2.5 Seismic Monitoring

GPS equipment and techniques provide a unique opportunity for earth scientists to study regional and local tectonic plate motions and conduct natural hazards monitoring. Modern low-cost, lightweight systems, which can be used in all weather conditions, provide geodetic precision (0.5-1.5 cm) with post-processed solutions on baselines that are tens to hundreds of kilometers long. Additionally, many researchers have used GPS to monitor volcanic deformation. USGS has been utilizing these techniques since 1990 to conduct a number of studies, including the monitoring of a network of points in and around Long Valley caldera. This is a site of volcanic and tectonic unrest that includes a high level of seismic strain release, rapid ground deformation, and an unusually high flux of magmatic carbon dioxide. The results of the studies demonstrate the usefulness of GPS as a monitoring tool. Such measurement campaigns can be used to develop models to improve our understanding of volcano-tectonic systems and the hazards they pose.

Relevant Facts

- USGS noted a substantial need for higher precision, higher density of observations, greater frequency of measurements.

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[13] Shrestha, Ramesh L. and Carter, Bill, March 1998, "Instant Evaluation of Beach Storm Damage Using Airborne Laser Terrain Mapping," ***EOM (Earth Observation Magazine)***, pp. 42-44.

- USGS currently uses vertical data to infer the location, orientation, and slip on active faults, the expansion and collapse of dikes, the location and volume of magma chambers. These studies are documented in numerous journal publications.

- NASA is currently funding a study on the crustal extension of the U.S. Basin and Range Province using survey-mode GPS geodesy.

- GPS surveys are generally used on all seismic studies. Additionally, GPS is often used for monitoring the movement of active faults, the reason why we need a reliable vertical system based on NAVD 88. Often, it is possible to determine the distances between stations, even over distances up to several hundred miles, to better than 5 millimeters (about a 1/4 of an inch).

- Because of subsidence and liquefaction, port facilities pose special problems for monitoring seismic activities, for example, finding a stable benchmark within the Port of Long Beach is a problem for seismic monitoring.

- Presently, the Port of Long Beach is establishing an automated monitoring system to study the impact of earthquakes on wharf structures. Because of liquefaction of soil, these structures are subject to damage during a major earthquake. The Port is interested in developing a system to monitor movement with structures in real-time during earthquakes, and developing better understanding of design measures to minimize damage. The instrumentation, installed on wharf structures and pylons, will consist of slope inclinometers, accelerometers, and piezometers; these instruments will be connected to a central computer. Two of the primary features the system will monitor are the lateral (horizontal) movement and the differential (vertical) movement of the features. GPS can be integrated with the system as one of the monitoring instruments; it could detect movement in three axes.

- Good vertical control is vital in locating and documenting damage after seismic events.

Discussion

The availability of a precise and reliable vertical reference datum is critical both for monitoring the on-going movement of the earth in areas of high seismic activity, as well as locating and assessing damage following major events. The City of Los Angeles, for example, had many problems and a great deal of uncertainty in evaluating locations of subsurface damage to utilities following the Northridge Earthquake of 1994. Major vertical change is a direct indication of subsurface damage. Being able to quickly monitor change is key to emergency response. Many of these problems had their root causes in the fact that there were not only different vertical datums within the Los Angeles basin, but that a great many of the vertical reference points (bench marks) the engineers and scientists were relying on had themselves become doubtful. This condition, which results from natural or artificially caused ground subsidence, is worsened when reference elevations are in error because of years of neglect.

Additionally, port facilities are areas of high risk during major seismic events. Due to liquefaction associated with the geology of a port or harbor location, it is absolutely vital to monitor all components of earth movement, including height. The added safety associated with the data would provide a higher level of safety and security to world trade.

Conclusion

Most users felt that it would be best if the NGS continues to conduct, archive, and distribute accurate and up-to-date height information on a yearly basis. Also, users felt that NGS should carry out research to foster the use of survey-mode GPS, real-time kinematic (RTK) GPS, LIDAR and IFSAR. The NGS, NASA, USGS, and NSF are all stakeholders in the need to improve the geodetic data available to the scientific and engineering communities.

Solar powered GPS receivers and antennas measure millimeter-to-millimeter movement of the earth's crust in the Nevada desert

Figure 5 GPS Receiver in Use for Seismic Monitoring

America will have cities safer from earthquakes if we obtain higher-quality, denser, and more precise geodetic data. This is critical to the development of design standards for public works structures and buildings, in order to make them more earthquake resistant and safer. The failure of a parking structure at a veteran's hospital during the

Sylmar earthquake of 1971 accounted for 108 dead. The collapse of Interstate 880 during the Loma Prieta earthquake of 1988 caused the death of many motorists. The toll would have been considerably greater if a World Series game was not in progress. The cost from the Loma Prieta and Northridge earthquakes to California's transportation network alone has exceeded 10 billion dollars. This does not take into account the loss of life, injury, and human misery caused from these recent quakes. More and greater earthquakes are merely a matter of time. When and where is critical. Again, precise and reliable spatial data give the seismologists and engineers the tools to develop reliable prediction algorithms, and to develop cost-effective earthquake resistant designs. All who live in earthquake and volcano-prone areas of the nation—California, North Carolina, Nevada, Utah, Idaho, Alaska, Missouri, Arkansas, Oregon, and Washington—will receive direct benefit.

3.3 Transportation Management

"Transportation Management" is defined herein to include marine navigation and safety; air navigation and safety; vehicle positioning and safety; and train positioning and safety. Elevation requirements for these applications are summarized in Table 2.

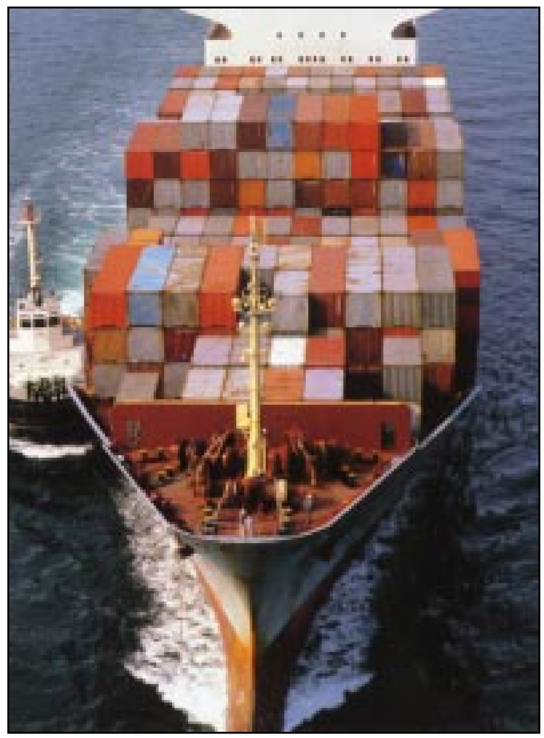
Elevation Requirements by Application:	DEM Vertical Accuracy	Static Elevations	RTK Elevations
Marine Navigation & Safety	**15 cm**	**2 cm**	**5 cm**
Air Navigation & Safety	**1 m**	**2 cm**	**15 cm**
Vehicle Positioning & Safety	**15 cm**	**2 cm**	**Horiz. only**
Train Positioning & Safety	**15 cm**	**2 cm**	**Horiz. only**

Table 2. Elevation Requirements for Transportation Management Applications

High-accuracy DEMs are required for Intelligent Transportation System (ITS) and Positive Train Control (PTC) applications. The land transportation community needs RTK horizontal positioning, but not RTK vertical positioning. High-accuracy digital bathymetry is required for marine navigation and safety; GPS-occupied tidal stations are needed to link bathymetry to the ellipsoid height system. All transportation applications require fixed features to be surveyed at the 2-cm accuracy level. The nautical community needs RTK positioning, at the 5-cm level, for positioning of dredges as well as ships, and to keep vessels from running aground. The aviation community needs RTK positioning of aircraft, at the 15-cm level, for final approach and Category 3 landings; whereas the elevations of the runway needs to be surveyed with 2-cm accuracy.

In addition to being an enabling technology for Automatic Vehicle Location (AVL) and Computer Aided Dispatching (CAD), differential GPS (DGPS) is also an enabling technology for the Intelligent Transportation System (ITS), as well as railroad, marine, and air navigation and safety. NDGPS can be used for control of cars, trucks, trains, dredges, ships, and private aircraft, without need for each user to establish single-purpose GPS reference stations. DOT estimates that thousands of lives can be saved annually by NDGPS through prevention of highway and railroad accidents alone.

3.3.1 Marine Navigation and Safety



Most of the port facilities in the United States are affected by tidal conditions that make navigation with large container ships difficult and hazardous. The ships need to be aware of under-keel clearance (relative to the channel bottom) and over-head clearance of the ship's superstructure (relative to bridges). Since timing of arrival and departure is critical in all shipping operations, it is important to have reliable height information on a real-time basis for the height of water and bottom of navigational channels. Correct height information can limit use of ballast with ships, an operation where water is used to lower the ship to draw more water. This operation is not only time consuming, but is also very expensive. Correct height information can also limit dependency on tidal conditions; waiting for the right conditions can cause unnecessary delay. In addition, height information is needed during docking operation because adequate clearance is needed for the operation of the crane for loading or unloading containers.

The U.S. Coast Guard (USCG) and the U.S. Army Corps of Engineers (USACE) have developed their current DGPS stations to support the navigation and safety needs of the maritime industry. Virtually all those interviewed expressed the attitude that the Federal DGPS stations have been a good investment as a basis for NDGPS. The USACE uses DGPS to accurately position dredges and to ensure that dredging is performed at the correct locations and to the required depths. Currently, ships rely on DGPS to determine their horizontal positions, but not their elevations. These DGPS stations will require a reliable height system to provide accurate vertical data.

Relevant Facts

- Marine navigation is currently dependent on a number of different height datums and definitions. Navigation of vessels, today and tomorrow, requires a common and reliable height definition.

- Use of various height datums is very confusing and can impact marine safety. Use of new navigational systems is dependant on GPS, radio links, and other motion sensors. Differential GPS (DGPS) can provide the pilot real time information on under keel and overhead clearance for the vessels entering a port with full cargo, or leaving the port empty. Using GPS, combined with other sensors, the pilot is able to determine the squat factor and the tilt of the vessel, and, thus, avoid damaging the keel.

- The GPS navigational instrumentation, used by the pilots and shipping industry, is dependent on reliable height data. Currently, the pilots are using heights derived via differential correction from the local vertical datum.

- Because there is currently no national height system, many ports, including the Port of Long Beach, have established a local geoidal model to deal with subsidence and hydrographic surveys.

- Port facilities are required to publish height information using the Mean Lower Low Water (MLLW) datum. Using this datum, height values are normally positive numbers. This might result in problems when different datums are in use in the same geographic area. For example, the City of Los Angeles publishes height values using Mean Sea Level (MSL) datum, while the Port of Long Beach publishes in MLLW. The difference between these vertical datums is clear to the Port of Long Beach surveyors, but may be confusing to others.

- The GPS is the “core” component of a modern marine navigation system providing navigational information on a real time basis. GPS networks were established to monitor height differences within some ports, a task that has been completed in past years by leveling. Leveling will still be part of the monitoring, but in a reduced role.

Discussion

The entire marine industry, including the Marine Academy, pilots, and shipping owners, must be involved in modernizing the navigational systems. The process must include a provision for education of new pilots and continuing education of current pilots and others involved in marine navigation.

Working with the Port of Oakland, NGS has proven that DGPS can provide real-time measurements of a vessel’s settlement, squat, trim, roll, pitch, and heading. Furthermore, DGPS can provide the position of a vessel’s keel in real-time to within 10 centimeters (4 inches) relative to the bottom of the shipping channel. This clearance is critical. Ships that only barely touch the channel bottom are stopped for several days for mandatory inspections. Depending on cargo, every additional inch of draft can be worth tens of thousands of dollars to shippers per voyage, so shippers are tempted to load their ships to the maximum. Ports with shallow channels lose business to competing ports with deeper channels. Representatives of the maritime industry unofficially estimate that NDGPS reference stations near ports and harbors would cause an annual increase of $16 billion in cargo value in domestic waters, and an annual increase of $640 million in tax revenue, or a $9.6 billion benefit over the projected 15-year life of the NDGPS.

There is currently no estimate on the cost of integrating a new height system with currently available marine navigation tools. Any costs to establish a modernized height system, and assure a safe marine navigational system, should be carried by all levels of responsibility, including the Federal government, shipping owners, and mariners.

Any action to improve marine navigation will also improve safety and efficiency. Free and safe passage of freight will benefit the local and national economy. On the other hand, a major accident within the marine industry due to navigational errors has the potential for disastrous consequences, with loss of life and loss of economic benefits.

Conclusion

The future of safe marine navigation is dependent on a modernized NHS. Local solutions are not adequate to meet the needs to deal with coastal and international navigation.

3.3.2 Air Navigation and Safety

Regardless of the GPS augmentation system used, high-accuracy DGPS surveys, called Area Navigation Approach (ANA) surveys[14], are used for 3-D surveys of Primary and Secondary Airport Control Stations (PACS and SACS), which provide control for various forms of airport surveys relative to NGS' Continuously Operating Reference Stations (CORS). Since CORS are assumed to have zero errors relative to the earth's center, airport surveys relative to the CORS effectively provide *absolute accuracy* rather than *relative accuracy*. DGPS procedures have been proven to be feasible for Category 3 (zero visibility) landings, as well as Category 1 and 2 landings. Furthermore, ground-based pseudolites[15] (essentially, GPS satellite transmitters that operate from fixed locations on the ground) could be well suited for such applications, but there are no official programs for pseudolite initiatives. The FAA is developing an alternative Wide Area Augmentation System (WAAS) for air navigation and traffic control purposes, designed solely for air safety. The WAAS uses a downlink from geostationary satellites with line-of-site communications to aircraft and air traffic controllers. ***Both the Wide and Local Area Augmentation Systems (WAAS and LAAS) are discussed in greater detail in the Appendix.***

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[14] Federal Aviation Administration, September 1, 1996, ***Standards for Aeronautical Surveys and Related Products***, FAA No. 405, Washington, DC, pp. 3.1-3.10.

[15] Cobb, Stewart, and O'Connor, Michael, March 1998, "Pseudolites: Enhancing GPS with Ground-based Transmitters," ***GPS World***, pp. 55-60.

3.3.3 Vehicle Positioning and Safety

The Nationwide Differential GPS (NDGPS), Automated Vehicle Location (AVL), and Computer-Aided Dispatch (CAD) capabilities are ideal for fleet control of buses, taxis, delivery trucks, etc. Cars equipped with GPS receivers are extremely popular in Japan and are becoming popular in the United States as well. <u>This translates into thousands of new jobs for Americans</u>. Current autonomous GPS procedures enable positions to be determined to 100 meters; with NDGPS, vehicles can be positioned in real-time with accuracy of several meters, with the vehicle's current location accurately shown on a digital road map on the dashboard. This capability also helps in dispatching police cars and tow trucks to accident sites. Furthermore, ITS, which relies heavily on DGPS technology, will enable many transportation innovations to be implemented, promoting time and cost savings, and public safety. For highway applications alone, the USDOT estimates NDGPS potential benefits of $8.388 billion over a 15-year period. ***DGPS applications for land navigation and vehicle tracking are discussed in greater detail in the Appendix.***

The Caterpillar Corporation estimates $60 billion per year in saving as a result of an estimated 12% increase in efficiency allowed by the use of RTK DGPS controlled construction equipment and survey techniques. Such increased production efficiency could benefit the U.S. $26 billion more in constructed transportation assets under the new 1998 ISTEA appropriation.

According to the Department of Transportation, auto accidents are expected to be the number 1 cause of deaths in America by the year 2020. Today, they rank fourth. ITS will promote transportation safety.

3.3.4 Train Positioning and Safety

The railroad industry has a potential to save millions of dollars every year once NDGPS is available to support the implementation of Positive Train Separation (PTS) and Positive Train Control (PTC). The Chairman of the National Transportation Safety Board, Jim Hall, reported in a public hearing that during the first half of 1996 alone, PTS and PTC could have prevented 35 railroad accidents resulting in 26 fatalities, 438 injuries, and over $60 million in damages. The Federal Railroad Administration (FRA), Project Sponsor for DOT's current NDGPS initiative, conservatively estimates NDGPS benefits of $67.34 million, over the estimated 15-year life-cycle of NDGPS, to the railroad industry alone. ***Combined with benefits to other industries, NDGPS has a benefit-cost ratio of 152:1.***[16]

3.4 Infrastructure Management

As defined herein, "Infrastructure Management" includes water supply and quality; subsidence monitoring; and stormwater/utilities management. Elevation requirements for these applications are summarized in Table 3.

Elevation Requirements by Application	DEM Vertical Accuracy	Static Elevations	RTK Elevations
Water Supply & Quality	**15 cm**	**2 cm**	**5 cm**
Subsidence Monitoring	**2 cm**	**1 cm**	**N/A**
Stormwater/Util. Management	**15 cm**	**2 cm**	**5 cm**

Table 3. Elevation Requirements for Infrastructure Management Applications

High-accuracy DEMs are vital for management of America's infrastructure. The Geographic Information Systems (GIS) for most state Departments of Transportation need elevation data for upstream and downstream ends of culverts, that pass under state roads and highways, for management of drainage systems as conditions change. Every community needs good elevation data as a high priority, because it is vital to the provision of water for local citizens and for stormwater drainage. Changes in elevation caused by subsidence are also vital for many communities, because subsidence threatens the continued supply of water. The 5-cm RTK elevation surveys are required for efficient survey of water, sewer, and drainage features.

3.4.1 Water Supply and Quality

Everyone knows that a sustained supply of safe drinking water is mandatory worldwide; but few Americans stop to realize the importance

[16] U.S. Department of Transportation, March 24, 1998, ***Nationwide DGPS Report***, Washington, DC, p. 64

of elevation data for wellhead protection, water supply and quality, flood protection, and management of natural systems that support hydrological and ecological functions.

Relevant Facts

Currently, states and local communities are required to comply with the Safe Drinking Water Act of 1997 (SDWA). However, they lack the elevation data necessary to effectively execute their responsibilities. The Southwest Florida Water Management District considers elevation data so critical to its mission that it is paying between $5,000 and $7,000 per square mile to obtain 1-foot contour data compiled photogrammetrically. This is roughly comparable to the LIDAR-generated DEMs, discussed later in this report, which cost approximately $500 per square mile when mass-produced. Availability of high-accuracy DEMs to the thousands of water agencies throughout the United States will undoubtedly improve services and reduce costs to the water consumer.

The 1986 Amendments to the Safe Drinking Water Act (SDWA)[17] established a Wellhead Protection Program (WHP) to protect ground waters that supply wells and well fields that contribute drinking water to public water supply systems serving 50% of all Americans and 95% of rural America. The wellhead protection area (WHPA) is ***"the surface and subsurface area surrounding a water well, or well field, supplying a public water system, through which contaminants are reasonably likely to move toward and reach such water well or well field."***

To comply with the SDWA, each State's WHP must:

- Delineate the WHPA for each wellhead
- Identify sources of contaminants within each WHPA
- Develop management approaches to protect the water supply within WHPAs from such contaminants

[17] U.S. Environmental Protection Agency, April 1989***, Wellhead Protection Programs: Tools for Local Governments***, EPA/440/6-89-002, Washington, DC, pg. 3.

- Develop contingency plans for each public water supply system to respond to well or well field contamination
- Site new wells properly to maximize yield and minimize potential contamination

Without high-resolution, high-accuracy DEMs, compliance with this mandate is essentially impossible.

Discussion

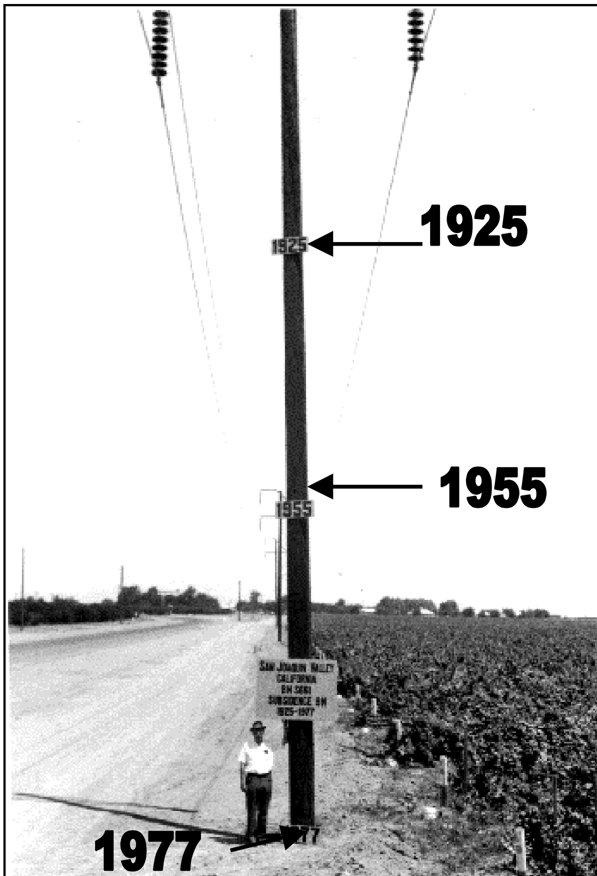
NAVD 88 values for survey control are not available in many areas. While NAD 83 horizontal positions are easily determined most everywhere, the same is not true for vertical.

For example, the California Department of Water Resources is currently building a small pipeline project in San Bernardino County. The NAD 83 horizontal positioning was determined in a cost-effective manner using GPS and the California Department of Transportation (CALTRANS) High Precision Geodetic Network (HPGN). The HPGN control points, equivalent to HARN stations, have GPS-derived horizontal positions; some have low accuracy vertical values. None of the HPGN points in the vicinity of the pipeline project have vertical values. Bringing NAVD 88 values into the area was too costly for the project, and a decision was made to use available NGVD 29 elevations with NAD 83 horizontal positions. Thus, high accuracy horizontal coordinates were merged with low accuracy elevations, diluting the overall effectiveness of the surveys. If there had been more economical means of providing NAVD 88 elevations, they would have been the preferred alternative.

3.4.2 Subsidence Monitoring

Land subsidence, the loss of surface elevation due to removal of subsurface support, occurs in nearly every state in the United States. Subsidence is one of the most diverse forms of ground failure, ranging from small or local collapses to broad regional lowering of the earth's surface. The major causes of subsidence include: (1) dewatering of peat or organic soils, (2) dissolution in limestone aquifers, (3) first-time wetting of moisture deficient low density soils (known as hydro-compaction), (4) the natural compaction of soil, liquefaction, and crustal deformation, (5) subterranean mining and withdrawal of fluids (petroleum, geothermal, and ground water).

During the recent five years of drought, the California Department of Water Resources estimates the state's aquifers were being overdrafted at the rate of 10 million acre-feet per year. Unfortunately, the results of overdrafting aquifers has led to many problems caused by land subsidence, including:



Approximate levels of subsidence. The signs show the position of land surface in 1925, 1955, and 1977. Although the rate of subsidence has decreased, the continued pumping of ground water has resulted in additional subsidence in the past 20 years.

Figure 6 Subsidence in California's Central Valley

- Changes in elevation and gradient of stream channels, drains, and other water transporting facilities
- Damage to civil engineering structures--weirs, storm drains, sanitary sewers, roads, railroads, canals, levees, and bridges
- Structural damage to private and public buildings
- Failure of well casings from forces generated by compaction of fine-grained materials in aquifer systems

- In some coastal areas, subsidence has resulted in tidal encroachment onto lowlands.

Relevant Facts

- In many areas of California and other states, the elevation data are obsolete and incorrect because of earthquakes, other crustal motions, and subsidence caused by withdrawal of groundwater and petroleum.

- NGS completed most major leveling projects in the 1960s through the 1980s, and many benchmarks have since been destroyed or subject to subsidence.

- Today, leveling between existing benchmarks in areas of subsidence reveal significant discrepancies between related benchmarks. Also, historical published vertical data (through the early 1970s) indicate substantial subsidence throughout the California Central Valley and other areas.

- The use of leveling to maintain vertical networks is labor intensive and cost prohibitive. With appropriate standards and procedures, GPS surveys provide a cost-effective method of establishing and maintaining vertical data. Organizations that have the responsibility for monitoring subsidence need the ability to rapidly and accurately determine orthometric heights over a large area.

- The USGS has abundant data and reports of subsidence caused from groundwater withdrawal. However, little or no recent elevation documentation is available over large areas. This is especially true of the San Joaquin Valley in California.

- Leveling is too expensive for most state agencies responsible for subsidence monitoring. The availability of a national height system would make the use of GPS feasible, both technically and economically.

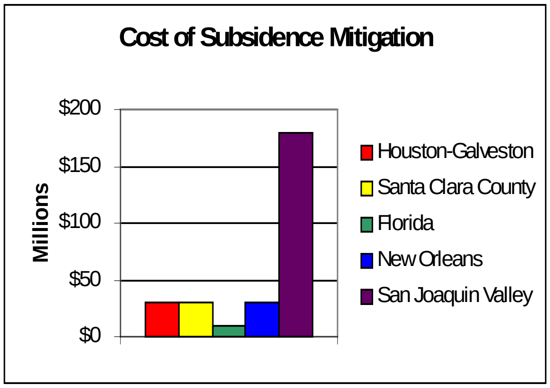


Figure 7 Annual Costs of Subsidence Mitigation

Discussion

The California Department of Water Resources estimates that it will cost approximately $1 million per year to establish an elevation network throughout the San Joaquin Valley for subsidence monitoring purposes. Numerous Federal, state and local agencies would share the cost. Federal agencies would include NGS, USGS, U.S. Bureau of Reclamation (USBR) and the U.S. Army Corps of Engineers (USACE). State agencies would include the California Department of Transportation and Department of Water Resources. Local agencies would include water districts, reclamation districts, and counties.

According to estimates by the USGS, not implementing such a network has an estimated annual cost of over $180 million for subsidence mitigation in the San Joaquin Valley alone. See Figure 7.

Nationally, actual costs of damage caused by subsidence and the subsequent costs to mitigate and prevent further damage are difficult to calculate. Figure 8 provides relative estimates on a state-by-state basis of initial damages caused by various forms of land subsidence. In addition to the damage estimates presented graphically, the National Research Council[18] conservatively estimated the annual costs due to increased flooding and structural damage to be in excess of $125 million. These estimates do not include loss of property value due to condemnation, and they do not consider increased farm operating costs (re-grading of land, replacement of pipelines, replacement of damaged wells) in subsiding areas. It is estimated that annual subsidence costs may be about $400 million nationally. As shown in Figure 7, annual costs of subsidence mitigation in selected areas are estimated as follows: (1) over $180 million per year for the San Joaquin Valley, California; (2) over $30 million per year for Santa Clara County, California; (3) over $30 million per year for the Houston-Galveston, Texas area; (4) $30

[18] National Research Council, 1991***, Mitigating Losses from Land Subsidence in the United States***, Washington, DC, National Academy Press

million per year for New Orleans, Louisiana, and (5) $10 million per year for the State of Florida.[19]

Conclusions

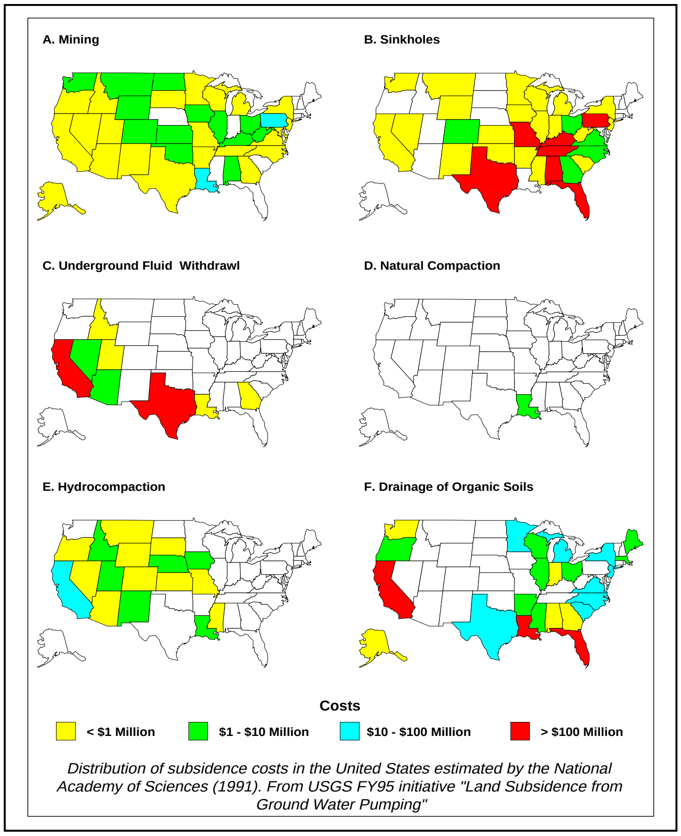


Figure 8 National Distribution of Subsidence Costs

GPS, combined with a precise, reliable, and accessible vertical network (NAVD 88), will provide a cost-effective method to accurately establish elevation data over large areas. Specific areas of concern are areas in which subsidence due to groundwater extraction, such as the San Joaquin Valley, is an on-going serious problem. The ultimate goal is to be able to rely on a national framework network, that would help state and Federal agencies better manage problem areas at a significantly lower cost to taxpayers.

3.4.3 Stormwater and Utility Management

Of all utility systems, stormwater management has the greatest need for accurate DEMs for efficient hydrologic and hydraulic (H&H) modeling of watersheds, streams, and channels. Hydrologic models predict volumetric concentrations of water from peak events (10-, 50-, 100-, and 500-year floods), and hydraulic models compute where those waters will go and how flood waters will back-up behind undersized culverts and bridges. These H&H models predict the extent and depth of flood

[19] National Research Council, ibid..

waters. They are vital for flood mitigation and proactive floodplain management. The LIDAR/IFSAR DEMs proposed herein would save the high costs of conventional stream cross-section surveys, and the DEMs would enable the accurate and efficient automation of the H&H modeling process. The nationwide acquisition of LIDAR and/or IFSAR-generated DEMs would save an estimated $200 million in conventional survey and H&H costs.

Stormwater, sewer, and water utilities all need accurate 3-D locations of underground pipes, manholes, drain inlets, fire hydrants, and similar utility features. DGPS surveys of the tops of manholes, grate inlets, etc., combined with manual measurements of invert offset elevations, are commonly used for GIS databases used in modern utility service agencies. In most cases, the NDGPS would not provide the 5-cm 3-D accuracy needed for this application; however, DGPS from a local reference station will satisfy this requirement. Alternatively, Washington D.C. and many other communities would be pleased to have 1-2 meter accuracy in horizontal positioning of manholes, fire hydrants, storm drain inlets, etc. (achievable from NDGPS) and 15-cm (6-inch) vertical accuracy of such features (achievable from the proposed DEMs).

The City of Miami is currently using RTK GPS technology to build a water utility information management system. Miami is flat. Its highest peak is just 40 feet above sea level, and its groundwater table is only 3 to 6 feet below the earth's surface. When it rains, this water table is close enough to get sucked into the city's aging sewer pipes, causing pipe and pump station failures that spill raw sewage onto city streets and into the Miami River.

EPA issued a directive requiring that the city overhaul its sanitary sewer system by 2002. The use of RTK GPS with accurate height information will not only help to solve the problem, but the field-inventory of the City's water and sewer facilities is going five times faster and costing up to 50 percent less compared to conventional utility-location surveys.

3.5 *Construction and Mining*

"Construction and Mining" is defined herein to include infrastructure construction (light or precision construction); mining and earth moving (heavy construction); and pipeline construction. Elevation requirements for these applications are summarized in Table 4.

The availability of a National Height System makes the use of technologies such as Real-Time Kinematic (RTK) DGPS positioning feasible for a variety of cost-saving applications in the mining and construction industries. Construction and mining equipment developers (e.g., Caterpillar Corp.) have proven that vehicles, controlled by DGPS and computer programs and relying on DTM, can achieve 3-D positional accuracy of 6 inches. Additionally, this technology offers major efficiency improvements and reductions in risk to human operators in dangerous situations. In some areas, autonomous earth-moving machines are already in operation.

Elevation Requirements by Application:	DEM Vertical Accuracy	Static Elevations	RTK Elevations
Infrastructure Construction	**15 cm**	**1 cm**	**5 cm**
Mining and Earth Moving	**15 cm**	**1 cm**	**5 cm**
Pipeline Construction	**15 cm**	**1 cm**	**5 cm**

Table 4. Elevation Requirements for Construction and Mining Applications

3.5.1 Infrastructure Construction

When 3-D coordinates (northing, easting, and/or height) are provided by the project engineer, as the locations for construction stakes, DGPS RTK techniques can be used to place the stakes accurately and efficiently. This process saves considerable time and expense in comparison with conventional construction surveys. Cost savings have not been computed by the survey industry, but savings could be in the billions of dollars annually. This technology essentially exists today, and it could be implemented in 3-dimensions, given the existence of a NHS.

Relevant Facts

- State transportation agencies require elevations primarily to design and construct state highway facilities. In many areas of California, for example, the elevation data are obsolete and incorrect as a result of earthquakes, other crustal motions, and subsidence.

- In most areas of California, the vertical component of the NSRS has not been maintained since the early 1970s. Some NAVD 88 leveling has been accomplished; however, large areas (e.g., the California Central Valley) remain without a reliable vertical datum. Because of this, transportation facilities are designed and constructed using local datums that conform to existing fixed works, rather than to either NGVD 29 or NAVD 88. (Note: the reference datum is often called NGVD 29; however, in actuality, the datum is a local datum because of the unreliable NGVD 29 bench marks.)

- The lack of a comprehensive NHS has also resulted in problems with road and bridge construction in many major cities in the United States. In Los Angeles, for example, of the 120 bridges, there have been serious engineering problems on approximately 30 bridges because of discrepancies in vertical data. The following three examples provide some background of this problem:

  - **Franklin Avenue Bridge** – The bridge is 6" lower on one end than the plans indicate, causing $150,000 in claims from the contractor. The total construction cost is $2.5 million.

High accuracy height information is critical in bridge construction

  - **Sunset Drive Bridge** – The city had to reestablish vertical control, because information had been obtained from a Caltrans benchmark instead of a city benchmark. The extra cost to the city was $30,000.

  - **Fourth Street over Figueroa** – The grade was off 20 feet from the vertical bench mark used. Piling holes are 20 feet deeper than they should be. The extra cost to the city was $600,000 on a $6,000,000 project.

In Los Angeles alone, according to a local official, the city estimates the total cost for vertical problems on all bridges to be $5 to $7 million.

- Different cities have different datums, and cities typically require that their datum be used when working in their jurisdiction. Chicago has approximately a dozen different vertical datums in use for various purposes. This creates the need for checking when projects cross jurisdictional boundaries. Rarely, if ever, is this budgeted for in the construction bid.

- GPS has been used successfully by surveyors to provide horizontal and vertical project control. Since a majority of highway projects are long and narrow, centered along an existing roadway or a proposed center line alignment, it is necessary to surround the projects with existing control points where possible. Because of the lack of a reliable height reference system, all projects require leveling of control points within the same time frame as the GPS campaign. Having a primary network survey, completed using GPS and leveling, provides a reliable reference network for design surveys providing vertical accuracy within 2-cm accuracy.
- The Minnesota DOT is presently testing GPS-derived elevations against more accurate elevations derived from precise leveling. Lessons learned include the need for a better geoid model, especially in areas where gravity anomalies are highest. Accurate calibration of the GPS signal phase center on the antennas is also critical.

Discussion

State and local government participants, along with GPS industry and consultants involved in precise positioning using GPS, expressed a critical need for a dense network of precise GPS Base Stations and 1-cm geoid modeling data. Generally, the requirements for the standard NHS were to support other technologies, to improve efficiencies, and to save costs both to the agencies and taxpayers.

Users commented that state and local agencies, together with the private sector, need to partner with the NGS to implement the pieces missing for the height modernization effort. The NGS should assume an active role as program manager for the establishment and maintenance of a modernized NHS.

The benefits of a modernized NHS would be dispersed broadly. Surveyors, engineers, mapping professionals, utility companies, farmers, home-buyers seeking Federally-guaranteed mortgages, and users of America’s transportation system—virtually every American—will derive benefits from NHS implementation.

Ultimately, the taxpayers save, and every American benefits, if the NHS is implemented.

In California, for example, the Department of Water Resources and other local and regional water and power entities will realize significant benefits from a modernized NHS. Critical to the development of California's transportation improvement projects, a modernized NHS would provide a consistent inter-relationship between projects. NHS will also facilitate consistent, statewide Geographic Information Systems (GIS) and exchange of related data.

Conversely, water agencies, port districts, and other entities requiring reliable vertical data will be adversely affected by continued neglect of the height system in California. Also, local GISs will not be standardized or interoperable, hampering the development of regional and statewide systems and the exchange of GIS data. To some extent, all engaged in engineering, earth science, planning, land development, and geographic information will continue to be adversely impacted. Costs will increase because of non-standardized procedures and duplication of efforts. Everyone suffers from less efficiency and a delayed implementation of height modernization initiatives.

Conclusions

Users consistently stated that the United States is lagging our competitors in realizing the full potential of GPS, a vital system developed by the United States. Other countries are moving forward rapidly (Japan, Sweden, etc.) while we are waiting for the leadership and funding of a national implementation plan for NAVD 88.

Users expressed the attitude that the Federal government should support nationwide implementation of NAVD 88. State and local agencies, and the private sector, should participate in densifying and expanding the "framework" system in cooperation with the Federal government.

The implementation of a NHS that would provide a resolution to a number of height related problems will help to contain costs on future large-scale projects. Less "checking and fixing" will be required to find and resolve discrepancies, as jobs will no longer have a vertical disconnect. Since there are so many unknown factors, the solutions lie with the Federal Government and private sector survey firms that can work to the same standards as the government.

3.5.2 Mining and Earth Moving


Modern mining and earth-moving equipment is increasingly guided by GPS, relying on accurate horizontal and vertical data

Computer-Aided Earthmoving Systems (CAES)[20] integrate DGPS with RTK positioning and control of construction vehicles. Construction vehicles are equipped with DGPS receivers, linked to Geographic Information Systems (GIS) with DTMs updated "on-the-fly" as earth-moving machines make their "cuts and fills." As each vehicle's onboard computer radios GPS-based position information back to a dispatch computer, the dispatcher monitors the location and status (full or empty, heading, and velocity) of each vehicle in the fleet, monitors where trucks are waiting to be loaded, and redirects them for maximum efficiency. Using the in-cab display, the earthmoving equipment operator views the design grade, with cut or fill requirements. Using a moving cut/fill isopach map as a guide, the operator can minimize push distances and increase efficiency. After the CAES machine has started its cut, the heading and a long section is displayed on the monitor, providing the operator with a graphical display of the current topography in relation to the design surface. As the operator makes the cuts, the onboard processor updates the current DTM in real time. This on-the-fly updating enables the operator to assess excavation progress for each individual pass and maximize productivity by receiving immediate feedback. All of these features have combined to produce a dramatic increase in the amount of useful work that construction and mining machines can accomplish each day.

[20] Long, James, March 1998, "Black Thunder's Roar: Mining for Solutions with RTK GPS, ***GPS World***, pp. 23-28.

Relevant Facts

- Most mine sites rely on local vertical and horizontal control systems that are established by the mining contractor. These systems are local and must be recreated at each mine.
- Since most mining operations are using a local system, all operations are controlled by it, including GPS.
- In some locations, GPS is currently used for all mine survey operations, including RTK GPS systems installed on bulldozers, trucks and graders[21].

Discussion

GPS is a vital link in the present and future operation of mines in the United States. It helps in all phases of the operation, from planning to restoration of the natural habitat to near its original condition. The use of GPS, for tracking locations and for control of mining equipment, requires the accurate height system that the national implementation of NAVD 88 would bring.

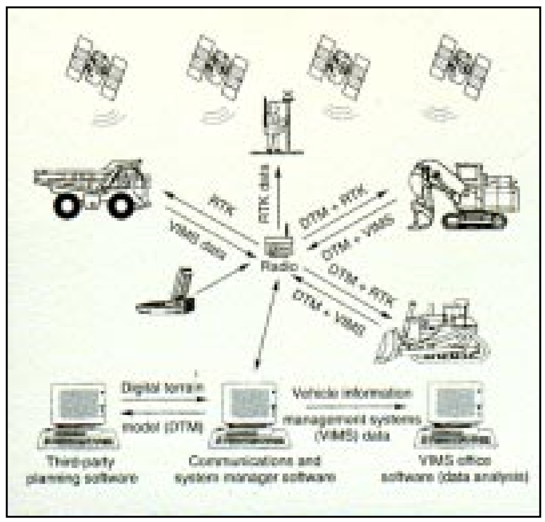


Figure 9 RTK DGPS for Construction and Mining

Real-Time Kinematic (RTK) DGPS positioning has many cost-saving applications in the mining and construction industries. Construction and mining equipment developers (e.g., Caterpillar Corp.) have proven that vehicles, controlled by DGPS and computer programs with DTMs, can achieve 3-D positional accuracy of 6 inches, with major efficiency improvements and reduced risks to human operators in dangerous situations. Some autonomous earth-moving machines are already in operation.

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[21] Long, ibid

The Caterpillar Corporation estimates* $ billions per year *in savings as a result of an estimated 12% increase in efficiency allowed by GPS modernization.

Conclusion

Implementation of the NDGPS, and/or upgrade of future GPS satellites as recommended below, could eliminate many (but not all) of the requirements for mining and construction companies to operate their own DGPS reference stations that transmit DGPS corrections to each vehicle. Instead, DGPS corrections would be received direct from the NDGPS beacons, or not needed at all with effective upgrades to GPS satellite frequencies. If cost benefits are anywhere near the $billions claimed, this should translate into reduced costs for future road construction and other expenses borne by American taxpayers.

3.5.3 Pipeline Construction

As with the other construction sectors, pipeline companies and construction contractors are increasingly using GPS as a survey tool for conducting surveys for new pipelines and for locating and maintaining existing pipes. Accurate location data are especially important for population density survey and for tracking facilities' locations and maintenance operations.

Relevant Facts

- Many pipeline companies are not comfortable with the present status of vertical control. This is especially the case in Southern California. For example, the Southern California Gas Company needs a reliable vertical datum, preferably using NAVD 88 definition, for its service area. Federal law mandates that they provide accurate maps for the locations of their gas lines and services. The inadequacy of reliable and consistent vertical references causes thousands of dollars in additional mapping costs each year for this utility alone.

- The use of GPS as the tool for engineering and right-of-way surveys has been increasing in recent years. However, the lack of a reliable vertical datum results in problems with heights. The solutions are usually made on a project-by-project basis, without consideration for the entire service area. While solving the immediate problem, these solutions are generally "stop gap" efforts that ultimately result in higher construction and system maintenance cost that are passed on to consumers in the form of higher rates.

Discussion

In general, the participants from the gas pipeline industry were satisfied with the results of their survey work. However, it would be desirable to have a more reliable height reference system in support of the operations since extensive work is being completed to establish a service area wide GIS to manage future operations.

The industry expects NGS to provide specifications and standards on a national basis. GPS is a common tool for most gas and pipeline company operations; the surveyors are dependent on good results. Therefore, uniform standards are important for all involved in providing surveying and engineering services.

3.6 Agriculture and Natural Resources

"Agriculture and Natural Resources" are herein defined to include precision farming; forestry; recreation; and environmental protection. Elevation requirements for these applications are summarized in Table 5.

Elevation Requirements by Application	DEM Vertical Accuracy	Static Elevations	RTK Elevations
Precision Farming	**15 cm**	**2 cm**	**5 cm**
Forestry	**1 m**	**N/A**	**Horiz. Only**
Recreation	**15 cm**	**2 cm**	**5 cm**
Environmental Protection	**15 cm**	**2 cm**	**5 cm**

Table 5. Elevation Requirements for Agriculture & Natural Resource Applications

Similar to the mining and construction industries, real-time kinematic (RTK) DGPS positioning has become vital for agriculture, forestry, environmental protection, and other applications related to natural resources. Farm machinery developers (e.g., Case, John Deere) are developing modern farm equipment with GPS guidance and/or autonomous control. All applications require DEMs with accuracy between 15-cm (6-inches) and 1 meter.

3.6.1 Precision Farming

With GPS-based precision farming technology, farmers have been able to go from farming by the acre to farming by the square foot, and they can reduce a major source of non-point pollution.

There is a sea change currently underway in the agricultural industry. New information technologies, with GPS data at their foundation, are changing farmers' relationship with the land, bringing them quite literally down to earth. The last revolution in agricultural technology, the development of chemical pesticides and fertilizers, brought farmers tools for mass-producing crops. This large-scale farming system treated fields uniformly: agricultural chemicals were distributed without regard to differences in soil content or plant health.

Perhaps more than any other application, the agriculture community will benefit from NDGPS. Over the projected 15-year life-cycle of NDGPS, estimated agriculture potential benefits total $3.436 billion.

The benefits of NDGPS for modern agriculture are well documented[22]. Precision farming systems gather data on tillage, seeds planted, weeds, insect and disease infestations, cultivation and irrigation, and *location-stamp* that data with GPS information. Using these data, farmers can micromanage every step of the farming process. For example, a farm GIS database might include layers on field topography, soil types, surface drainage, sub-surface drainage, soil testing results, rainfall, irrigation, chemical application rates, and crop yield. Once this information is gathered, farmers can analyze it to understand the relationships between the different elements that affect crop yields.

This new trend in "site specific" farm management is made possible by the merging of several unrelated technological advances. These include the personal computer, GPS, GIS, automated machine guidance, infield and satellite remote sensing, and telecommunications.

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[22] U.S. Department of Transportation, March 24, 1998, ***Nationwide DGPS Report***, Washington, DC, pp. 60-62.

Precision agriculture enables farmers to implement *Best Management Practices (BMPs)* through the careful control of the quantity of water, fertilizer and pesticides placed on different areas of land, depending upon soil type and condition, slope, and other factors. Height data have special relevance because slopes determine the direction in which runoff will flow, and runoff could adversely impact unintended areas. For these reasons, the agriculture industry needs good vertical and horizontal control and accurate Digital Elevation Models (DEM).

In recent years, the application of DGPS and DEM technologies has had the added benefit of reducing the quantity of herbicides, insecticides, and fertilizer. This has led to a decrease of the adverse environmental impact of these products. Additionally, the more effective use of insecticides, herbicides, and fertilizer has led to the decreased use of these products and increases in farm productivity, and has a direct impact on water quality and soil conservation. The reduction in the cost to produce foodstuffs will be carried to the consumer in lower costs for higher quality and safer food.

The fact that spatial data will need better registration may add a significant cost to the end user. At the present time, agriculture in general is working on a relatively thin margin, and any added costs in the start-up phases may make the use of precision agriculture prohibitive in many situations. This has implications for the degree of agricultural pollution and resource utilization/efficiency. However, in the long-term, the use of accurate vertical and horizontal data, and registered spatial information, will provide benefits through increased productivity, lower production costs, and lower prices for the consumer.

Using precise farming technology, fertilizer and herbicide application rates are changed on the go, improving yields and lowering costs.

Conclusions

In the long-term, the profitability of precision farming technology depends on the development of management systems that link inputs applied with yields harvested on specific sites. These management systems will be some combination of computerized decision support systems and the accumulated wisdom of experienced managers. History shows that most of the benefits of any new agricultural technology go to the early adopter. Those who lag have often been forced out of farming. Precision farming is expected to follow the same pattern. Those who begin to accumulate data and experience now will be ready to use improved precision technology as it matures.

Down to earth: Farmers measure crop yield by square foot instead of square acre using GPS-based precision farming technology

Similar to the mining and construction industries, RTK DGPS positioning has become vital for agriculture, forestry, and environmental protection. Farm machinery developers (e.g., Case, John Deere) are developing modern farm equipment with GPS guidance and/or autonomous control.

3.6.2 Forestry

During the estimated 15-year estimated life-cycle of the NDGPS, the U.S. Forest Service (USFS) estimates that the NDGPS will yield net savings of $6.83 million for command and control of fire-fighting alone.[23] With real-time DGPS to support GIS databases and digital maps, the fire mitigation plan can be better conceived and executed. Fire tanker aircraft, equipped with airborne GPS, could place fire retardant chemicals more accurately and efficiently, avoiding the unnecessary overlap of retardant drops over the same areas. DGPS is well suited for this application since no geographic landmarks are necessary to identify location.

Accurate DEMs (NAVD 88) are also needed for forest management because fires burn upward, and computer models of wild fires are based on slopes, timber height, aspect, and wind direction.

[23] USDOT, ibid, pp. 54-56

Using real-time DGPS for controlling retardant drops and target efficiency will result in 10% savings of retardant mixture. Moreover, DGPS technology enables both ground and air firefighters to communicate their locations accurately. This will save lives!

3.6.3 Recreation

Accurate DEMs are required for design and management of golf courses and ski resorts. DGPS positioning of snow grooming equipment is used for grooming to designed snow depths at ski resorts, but NDGPS beacons would normally be too far away to provide the needed 3-D accuracy; therefore the most modern ski resorts already operate their own DGPS reference stations. Casual recreational users of GPS receivers, with no requirement for elevation data, can use very inexpensive GPS receivers to enhance their recreational activities. For instance, fishermen can use them to determine locations of favorite fishing areas in the ocean, and hikers can use them to locate their position in remote wilderness areas. The USACE, National Park Service (NPS) and U.S. Forest Service (USFS) use DGPS surveys, for example, to accurately survey key features in recreational areas and/or to monitor the location of vehicles that often operate in remote locations. Although recreational users would benefit from high-accuracy DEMs and NDGPS, these benefits are incidental to those obtained for other applications indicated.

3.6.4 Environmental Protection

Recognizing the importance of GPS technology, EPA has a GPS Working Group responsible for developing GPS solutions to EPA requirements. Most requirements from EPA, state, and local environmental control officials are for horizontal positioning, but two specialized requirements for elevation data are identified below.

NDGPS is needed by EPA, state, and local officials to survey horizontal locations of hazardous materials (HAZMAT) incidents, oil spills, and contaminated water wells accurately and expeditiously. NDGPS would expedite damage assessment, quantification of contaminated areas, and clean-up actions. In the case of HAZMAT spills, time is very critical in assessing the situation and conducting the clean-up process. EPA has learned that real-time DGPS takes only 50% of the time for doing the same surveys as when post-processing is used. Also, there is a time savings associated with returning to and finding a specific site, e.g., for resampling of soils or contamination sites. EPA estimates net 15-year savings of $6.33 million, based solely on the benefits of using real-time DGPS as opposed to post-processing data as at present.

For a second EPA requirement, elevations of water wells are required to 1/100th of a foot, exceeding the vertical accuracy afforded by GPS technology; for this application, leveling will still be required, but it is effective only over short distances.

3.7 USGS National Mapping Program Evaluations

In 1994, the USGS National Mapping Division conducted an extensive evaluation of user needs for selected current products. The following user evaluations were extracted from the USGS Open-File Report 95-201. See:

http://mapping.usgs.gov/www/external/OF95-201.html

3.7.1 User Evaluations of NAVD 88 – from USGS Open-File Report

Of 2,130 respondents, 41.1 percent of the users indicated that it was important that USGS modify its data to reflect NAVD 88. Organizations with the highest percentage of requirements for NAVD 88 included: (1) city, town, and local governments, (2) county and regional governments, (3) and private industry. Users with the lowest percentage of requirements for NAVD 88 were nonprofit organizations. Users with the highest need for NAVD 88 indicated GPS applications; users with the lowest need for NAVD 88 indicated sales and marketing applications. Of those indicating requirements for NAVD 88 on USGS products, 31.4% indicated that contours and elevation data should be recompiled from NGVD 29; and 68.6% indicated that USGS should supply the shift algorithms or parameters to allow individual users to shift the data to satisfy their requirements.

3.7.2 User Evaluations of DEM Accuracy – from USGS Open-File Report

7.5-minute DEM Accuracy	Number	Percent
1 = Seldom meets needs	**27**	**2.8**
2	**93**	**9.6**
3 = Sometimes meets needs	**343**	**35.3**
4	**388**	**40.0**
5 = Always meets needs	**120**	**12.4**

Table 6. User Satisfaction with 7.5 Minute DEM Accuracy

30-minute DEM Accuracy	Number	Percent
1 = Seldom meets needs	**21**	**4.2**
2	**115**	**23.2**
3 = Sometimes meets needs	**204**	**41.2**
4	**111**	**22.4**
5 = Always meets needs	**44**	**8.9**

Table 7. User Satisfaction with 30 Minute DEM Accuracy

1-degree DEM Accuracy	Number	Percent
1 = Seldom meets needs	**36**	**8.1**
2	**124**	**27.9**
3 = Sometimes meets needs	**155**	**34.9**
4	**91**	**20.5**
5 = Always meets needs	**38**	**8.6**

Table 8. User Satisfaction with 1 Degree DEM Accuracy

These statistics generally substantiate the opinions expressed during the user needs assessment portions of this NGS study.

3.7.3 Evaluation of DEMs from LIDAR and IFSAR Sensors

In 1994, USGS was asked to perform the Method, Accuracy, Reliability, and Applications Test (MARAT) project to test the Light Detection and Ranging (LIDAR) system, under development at the Houston Advanced Research Center (HARC) in cooperation with FEMA and NASA, and the Interferometric Synthetic Aperture Radar for Elevation (IFSARE) system being developed at the Environmental Research Institute of Michigan (ERIM) in cooperation with the U.S. Army Corps of Engineers

(USACE) Topographic Engineering Center (TEC). USGS was requested to test the systems because neither FEMA nor TEC considered it appropriate to test their own sponsored systems. This study addressed one of the desires stated by General Gerald E. Galloway of the USACE who chaired the Interagency Floodplain Management Review Committee (IFMRC) assigned " . . . to make recommendations . . . on changes in current policies, programs, and activities of the Federal Government that most effectively would achieve risk reduction, economic efficiency, and environmental enhancement in the floodplain and related watersheds" (IFMRC, 1994). General Galloway stated, "As indicated in our report, during the course of our review, we determined that several agencies of the Federal Government were working towards development of data that would support digital elevation models. These agencies would include FEMA and NASA, using LIDAR; USGS using conventional mapping methods and remote sensing; and several elements of the Department of Defense using overhead platforms."

The MARAT project covered a 3- x 3-km area centered at the west side of Glasgow, Missouri, damaged during the 1993 floods. Results are well documented[24] Since 1994, both LIDAR and IFSAR sensors have made significant technological improvements to penetrate tree cover and acquire elevations of the ground rather than tree tops.

[24] Canfield, Dan, 1996, ***Digital Elevation Model Test for LIDAR and IFSARE Sensors,*** U.S. Geological Survey, National Mapping Division, Open-File Report 96-401.

4 – CASE STUDIES

4.1 Cost Savings from GPS vs. Traditional Surveying/Leveling

This chapter includes a compendium of elevation survey case studies containing lessons learned regarding the transition from leveling to GPS 3-D surveys. These case studies are summaries of detailed reports submitted to NGS from users in the field. Most of these surveys were performed prior to NGS' publication of its GPS elevation survey guidelines in 1997[25]. Results of these projects often contributed to the formation of or validation of those guidelines, then in draft form at NGS.

Variable Cost Savings from GPS

• **Post Hurricane Elevation Surveys**	**90%**
• **Post Earthquake Elevation Surveys**	**66%**
• **Water District Elevation Surveys**	**75%**
• **Crustal Motion Monitoring**	**99%**
• **Subsidence Monitoring**	**45 - 75%**
• **GPS RTK Construction Surveys**	**26 - 71%**
• **County- and City-wide 3-D Control Surveys**	**26 - 80%**
• **Topographic Mapping for Reservoir Construction**	**71%**

[25] National Geodetic Survey, November 1997, ***Guidelines for Establishing GPS-Derived Ellipsoid Heights (Standards: 2 cm and 5 cm), Version 4.3***, NOAA Technical Memorandum NOS NGS-58.

4.2 Disaster Response and Recovery

4.2.1 Hurricane Fran (North Carolina, September 1996)

Reported by:
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Woodbridge, Virginia
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Purpose

To assist FEMA in rapidly responding to Hurricane Fran, which impacted the North Carolina coastline on September 6, 1996, four separate quick-response GPS projects were performed, to 5-cm 3-D accuracy requirements, including the following:

- Survey high water marks along 150 miles of coastline for modeling of storm surge. This was needed to distinguish buildings damaged by winds (insured by homeowner policies) from those damaged by water (covered by flood insurance only).
- Survey transections across Topsail Island for a revised Flood Insurance Study (FIS). An expedited revision was warranted because of major changes in topography, including the loss of protective dunes. The revised FIS would impact construction codes for rebuilding.
- Survey horizontal location, lowest floor and lowest adjacent grade elevations of approximately 1,000 units, mostly duplexes, on Topsail Island. These surveys were vital for production of approximately 2,000 GPS Elevation Certificates, 24 damage assessment maps, and GIS databases required by FEMA Region 4 in Atlanta and FEMA's Disaster Field Office in Raleigh.
- Survey pilings on eleven buildings selected for evaluation of why some pilings failed and others did not.

Accuracy and Cost Comparisons

In four days, GPS static surveys were completed for 54 high water marks along 150 miles of shoreline, costing $14,530, or $269.07 per point on average. At an estimated $1,000 per mile, leveling would have cost $150,000. Therefore, the cost saving from GPS was approximately 90%.

In seven days, GPS "stand-off" elevation surveys were performed for 457 buildings, including lowest floor and lowest adjacent grade elevations for each. Because of duplexes and other multiple buildings, these 457 surveys resulted in the production of nearly 1,000 GPS Elevation Certificates, for individual addresses, by Dewberry & Davis, the prime contractor (see example at Figure 10). The survey costs averaged $43.15 per building.

Figure 10 GPS Elevation Certificate (Post Hurricane)

In four days, 22 new GPS temporary benchmarks and 135 intermediate “break points” were surveyed for 11 transections which crossed Topsail Island from the ocean to the intercoastal waterway. The “break points” were surveyed from the temporary benchmarks using a robotic theodolite. The average cost for each of the 157 points was $79.31.

In three days, 139 points were surveyed for the piling study, at an average cost of $42.82 per point.

Lessons Learned

- GPS is ideal for post-hurricane surveys because local control points are often buried under sand or rubble, and needed control can be rapidly extended over considerable distances.
- GPS temporary benchmark pairs, combined with a robotic theodolite, enable a single surveyor to survey hundreds of 3-D coordinates daily.

Most problems pertained to inaccurate GIS databases and lack of geocoding for tax parcels. Even though the GPS elevation surveys were completed in one week, it took several months to "sort out" the correct address and owner of the surveyed buildings for production of GPS Elevation Certificates. This was partly caused by the fact that a new E-911 addressing scheme was being implemented, numerous posted addresses did not match those in the county's database, and many address numbers were not posted on the buildings (or had been destroyed by the hurricane).

Highlights

One GPS team surveyed 150 miles of tidal surge high water marks in four days. At an estimated one mile per day, leveling would have required 150 days, and the client wouldn't know the horizontal coordinates (latitude/longitude) of the high water marks. At approximately 10% the cost of leveling, GPS provided superior results and expedited relief to hurricane victims.

Using GPS "stand off" elevation surveys which combined GPS and traditional surveying, 3-D surveys for 457 buildings were performed in one week. With traditional survey methods, it would have required nearly a week to extend control from the two nearest undamaged benchmarks on the other side of the intercoastal waterway before traditional surveys of individual buildings could have begun.

4.2.2 Northridge Earthquake (California, January 1994)

Reported by:
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Purpose

To rapidly restore the geodetic control network necessary for rebuilding roads, bridges, utilities, and other infrastructure damaged by the earthquake.

Background

The January 1994 Northridge earthquake permanently deformed the ground surface in the San Fernando, Simi, and Santa Clarita Valleys and in the northern Los Angeles basin. The force of the 6.8 earthquake raised the elevation of ground by as much as 20 inches (50 cm) and changed horizontal positions by as much as 8 inches (20 cm). This caused the network of permanent geodetic and survey control points, used by engineers and surveyors, to become distorted and rendered inaccurate. The transportation infrastructure within the area was severely damaged and many of the vital transportation links joining major areas were cut and emergency measures were put in place to reroute traffic and to plan a long term repair of damaged bridges, structures, and roadways. After the area was declared a major disaster area, the California Department of Transportation (Caltrans), with funding from FEMA, started the recovery work, which would last ten months. Topographic and design surveys were immediately carried out to provide engineers the vital data to plan and design the repair work. During these surveys, it was confirmed that the essential horizontal and vertical survey control had been distorted and made unreliable for these engineering and design purposes. Therefore, it was necessary to use localized survey control for individual projects and start planning for solutions to restore the area wide horizontal and vertical geodetic control. Without this precise and reliable control net there would be chaos in all future design and engineering projects.

Highlights.

This project demonstrated that GPS techniques cost 66% less than traditional survey techniques for reestablishing the entire horizontal and vertical control networks following the Northridge earthquake in 1994.

Approach

To seek a solution to this problem, Caltrans joined in a cooperative agreement between the National Geodetic Surveys (NGS), U.S. Geological Surveys (USGS), and the Federal Emergency Management Agency (FEMA) to rebuild the geodetic infrastructure in the Los Angeles basin. In addition to restoring the geodetic survey control, this project provided a unique opportunity to use GPS combined with precise leveling in a multi-disciplinary scientific study. This would be the first time such an approach was undertaken in the United States. This project would also provide critical data to investigate and analyze the geophysical aspects of an earthquake using GPS-based geodesy; to develop standards and specifications for maintaining vertical control through the use of GPS; and to analyze errors in GPS heights relative to geoidal models.

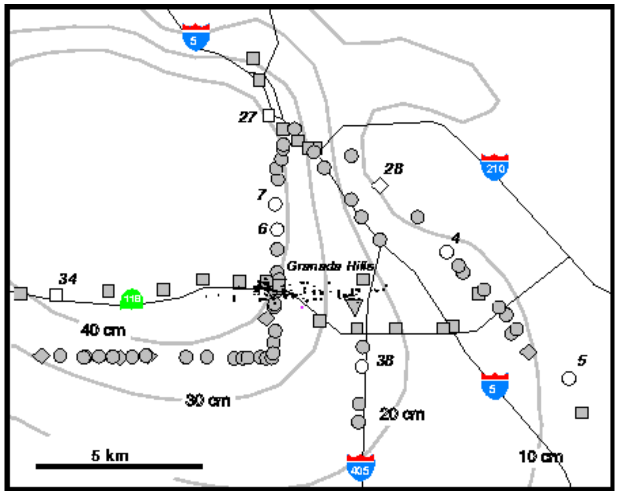
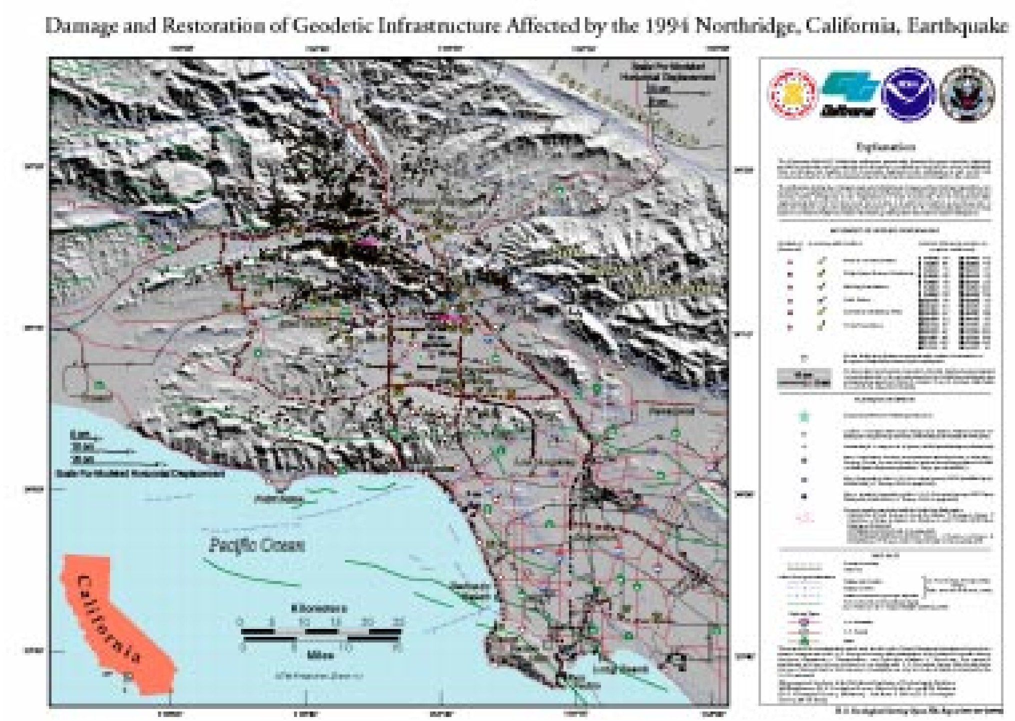


Figure 11 Observations from GPS-based Earthquake Analysis

The USGS was the lead agency, responsible for reporting to FEMA, analyzing historical geodetic data from 1974, and providing GPS observations for the horizontal network. The NGS was responsible for first order leveling observations, analyzing distortion in the national geodetic framework and developing standards and specifications for GPS derived heights and leveling. Caltrans was responsible for providing leveling along historical freeway routes, providing GPS observations for vertical control, and providing logistical support to other agencies.

Caltrans' internal engineering and survey resources were not adequate to meet the short-term needs of this project. All of the Caltrans staff was absorbed in performing damage assessments and conducting emergency repairs. To carry out this project in the required time frame, Caltrans contracted with the private sector to provide additional survey staff and technical resources. All survey consultants were assigned to various construction sites to support repair and reconstruction activities, including GPS surveys and traditional leveling.

The NGS staff recovered over 1000 benchmarks and performed over 1,500 km of leveling during a three-month period. Caltrans installed new benchmarks on a number of key structures to assist in future engineering studies. The leveling, where appropriate, was performed using a motorized leveling technique, developed by the NGS, using first order specifications and procedures.



Caltrans recovered and/or established 120 benchmarks along their transportation corridors that were suitable for GPS observations. This included a number of benchmarks used by the NGS for the first order leveling. All new monuments were installed in bedrock, bridge abutments and other stable engineering structures. Where this was not possible, deep-rod monuments were installed in conformance with NGS specifications. The GPS height observations were conducted using 12 to 15 Trimble 4000 SSE dual frequency geodetic receivers with 2.5 to 3.0 hour observation times. All baselines were observed twice using a different satellite constellation, different survey personnel and receivers each time. The baselines were reduced using the precise satellite orbit ephemeris, and network closures were completed to validate the integrity of the data. Final adjustment of the network was completed with ties to continuous tracking GPS stations and Very Long Baseline Interferometry (VLBI) control stations, using the vertical data derived from the NGS vertical control network.

Figure 12 Geodetic Damage/Restoration Following the Northridge Earthwuake

Findings

- It is critical to have precise and reliable vertical and horizontal survey control on or within major engineering structures and along transportation corridors. Proper and timely engineering and design activities rely on this control.

- statistical data on the performance of the structure immediately after a major disaster. Precise and reliable vertical data provide the engineers critical, historical data on the performance of the structure. This is essential for future earthquake resistant designs and retrofitting of existing structures.

- Integration of GPS and precise leveling have provided a valuable means for Caltrans to reliably and economically maintain and restore geodetic control if /or when another major earthquake takes place in the Los Angeles basin. It is estimated that the level of effort required to reestablish the entire horizontal and vertical network using GPS techniques is approximately 66% less than using conventional survey techniques. This major reduction of effort and cost is made possible by the use of GPS survey technology in conformance with NGS Guidelines for Establishing GPS-Derived Ellipsoidal Heights. The Northridge project was one of the projects used by NGS to define these standards, published in 1997.

- The number of primary control monuments can be reduced considerably by using GPS techniques. Leveling requires a stable monument every 1-km along a level route. In using GPS for vertical control, the spacing of monuments can be increased to a 5-km interval. However, for project control, it is desirable to have additional control since the control values can be published for horizontal and vertical components.

- GPS derived heights are accurate within 2 cm (3/4 inch) using the NGS guidelines. This accuracy is adequate for engineering projects over large areas since the relative accuracy between control points is greater than 2 cm. Geodetic leveling is still needed to meet the 1 mm accuracy specifications for First Order vertical control.

Conclusions

The use of GPS provides a reliable and cost effective technology for the engineers, geologists, geophysical engineers, mappers and surveyors in assisting with emergency recovery activities associated with major earthquakes or geological events, such as slides and erosions.

Southern California needs a reliable height reference network to help in development and maintenance of major transportation facilities. This will not only be vital to support present engineering work, but is more important to assist in fast recovery during major disasters.

For the use of GPS derived heights to be possible and effective, there must be one common, reliable, and accessible vertical reference datum. This eliminates the doubt or ambiguities that can arise when determining the effects of a geological event; e.g., did the surface of the earth move or was the vertical datum or control station in error?

This common reference datum should be based upon a national standard, as opposed to a local datum. This allows the GPS height observations, within the area of the geological event, to be referenced to geodetic height control stations well outside of the affected area. This is critical to the understanding of crustal movements and planning for future events.

4.3 GPS Elevation Surveys for Infrastructure Management

4.3.1 Metropolitan Water District of Southern California

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Purpose

The GPS-derived Ellipsoid Heights Program was initiated as an "earthquake insurance policy" for the Metropolitan Water District's vertical control investment and to guarantee the reliability and recoverability of the extensive vertical system without re-measuring the entire network.

Background

Metropolitan supplies water to Southern California through a distribution system consisting of 775 miles of pipeline, 243 miles of aqueducts, five filtration plants, eight reservoirs, and 15 hydroelectric power recovery plants, and (with NGS) had previously run over 800 linear miles of level lines to NGS first order standards. Upon receipt of NGS' 2-cm Guidelines for GPS-Derived Ellipsoid Heights, Metropolitan began re-surveying existing benchmarks to 7 kilometer spacing throughout the project area because major seismic events could significantly delay capital improvement projects and cost Metropolitan a great deal of money in down time (about one million dollars a day for Eastside Reservoir alone). Aqueducts, canals, pipelines and reservoirs require accurate vertical information for proper construction and operations. Systems such as these must be built to exact specifications to guarantee water distribution at the proper hydraulic gradient to control pressure and flow rates. The framework for Metropolitan's vertical network are the Continuous Operating Reference Stations (CORS) and the High Precision Geodetic Network (HPGN), established by Caltrans and NGS.

Accuracy and Cost Comparison

Metropolitan compromised on strict compliance with NGS' 2-cm GPS guidelines by:

(1) Not using fixed-height tripods

(2) Not collecting meteorological data

(3) Not using precise ephemeris on the network baselines.

Even with these compromises, rms values from GPS-derived orthometric heights (using NGS' Geoid 96 gravity model) did not exceed 2.5-cm when compared with traditional first-order leveling.

Thirty benchmarks covering 150 miles of leveling were used for comparison. The project report indicated that there was "a time savings of about a 4:1 ratio by using GPS versus leveling. However, it must be noted that in this particular example leveling does provide a more accurate final product. The need for this accuracy over large areas is debatable for most applications other than water delivery systems."

Lessons Learned

Regarding orthometric heights, "Metropolitan concludes that GPS-derived ellipsoid heights and the Geoid 96 model are very good tools to derive orthometric heights and can be used for most survey applications. However, they would not be sufficient for providing vertical control for construction of much of the water-related infrastructure."

Highlights

Time savings of about 4:1 was achieved by using GPS versus leveling. However, leveling accuracy was superior for orthometric height determination.

Pre earthquake GPS surveys provide "earthquake insurance" for cost-effective reestablishment of 3-D control following a major seismic event.

Regarding ellipsoid heights, "Metropolitan is very satisfied with this new vertical measurement tool because it will help us recover from any major seismic catastrophes in a short period of time. This can save us a great deal of money due to construction delays and survey control uncertainties. We also believe that in time, the geoid model will become more and more accurate as to become statistically predictable for use in orthometric height determination for nearly all applications of surveying and engineering."

NGS' GPS procedures and guidelines prove valuable to Metropolitan for three reasons:

- "Reliable elevations can be created in the fraction of the time through GPS vertical surveys, provided spacing of these benchmarks are kept at about 25 kilometers and the geoid model used is fairly accurate. Proximity to major mountain ranges needs to be avoided."
- "Accurate geoid heights can be created at a particular point if both the elevation above sea level (orthometric height) and the ellipsoidal height is known accurately. This information can then be used to re-establish a benchmark's position after a seismic event."
- "Large areas can be measured after an earthquake with GPS quickly to analyze the extent of the seismic event and intelligent decisions can be

made as to where leveling should be rerun over certain regions for design and construction purposes."

4.3.2 Greensboro (NC) Storm Water Services

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Purpose

To survey and inventory all stormwater infrastructure features, using GPS RTK procedures (required vertical accuracy of 5-cm at the 95% confidence level), to populate the Stormwater Management GIS. A preliminary requirement was to establish a survey control network, using GPS static surveys, with one pair of monuments per square mile city-wide (required vertical accuracy of 3.5-cm), "blue-booked" for entry in NGS' National Spatial Reference System (NSRS). Leveling was to be used when points were not "GPS-able" or to resolve discrepancies detected during the QA/QC process.

Figure 13 Measuring Invert Offsets for a GPS RTK Survey of Sewer Pipes

Accuracy and Cost Comparisons

GPS static surveys were performed for a total of 209 monuments. The average cost per monument was $369.42, excluding "blue booking" costs. These control surveys had no unusual difficulties.

Based on the control surveys, RTK surveys were subsequently performed for a total of 8,682 storm drainage features. The average cost per RTK point was $13.20. Although horizontal coordinates proved to be accurate,

The upstream and downstream node elevations for each sewer pipe are checked in the GIS for correct connectivity and flow direction.

If the downstream node is higher than the upstream node, or if the slope of the pipe is too great, the GIS tells us that something is wrong with our elevation data.

approximately 2% of the elevations were found to be in error by more than three feet compared with the DEMs, for reasons then unknown, causing all GPS heights to be suspect. Such errors were too large to be attributed to potential errors in the geoid model. All storm drainage features were resurveyed using leveling to assist in the error analyses.

Leveling was performed for all storm drainage features for comparison with GPS-derived orthometric heights. The average cost per point was $15.28, but leveling alone would not have provided the 3-D coordinates needed, so a direct cost comparison is inappropriate.

Figure 13 shows the final step of the stormwater survey and inventory process. After the top center of the catch basin manhole cover has been surveyed in 3-dimensions using GPS RTK procedures, the manhole cover is lifted, the invert offset is measured down to the lowest flow level of each pipe inside the manhole. This is necessary for calculation of invert elevations for upstream and downstream nodes of each sewer pipe.

GIS database attributes are entered into the pen computer, pre-programmed with "pick-lists" for over 20 items maintained in the GIS. Also, digital photographs are linked to the GIS file for any stormwater feature that is non-standard or unusual in any way. Other stormwater system GPS surveys include stream and channel cross-sections,

Highlights

At $369.42 per monument, GPS static surveys of 209 survey monuments achieved 3.5-cm vertical accuracy requirements.

At $13.20 per point, GPS RTK surveys of 8,692 storm drainage features achieved 5-cm vertical accuracy requirements approximately 98% of the time, and failed to achieve this requirement 2% of the time. Compliance with subsequently-published NGS 5-cm guidelines would have required each point to be surveyed twice, on different days, at approximately double the cost. Funding was not available for this.

At $15.28 per point, leveling was performed to assist in the error analysis of GPS elevation surveys, but leveling alone would not have provided the latitude and longitude needed for the storm drainage features. Therefore, a direct cost comparison between GPS and leveling is inappropriate.

and special bridge and culvert surveys for hydraulic analyses in floodplain modeling.

Lessons Learned

Because of cost constraints, the firm did not observe each point twice, on different days, as now recommended by NGS' 5-cm guidelines for GPS elevation surveys, subsequently published in November of 1997. Instead, heights were compared with the city's DEM as a QC check. This check was effective in identifying systemic errors, but not in preventing them.

Trimble Corp. evaluated all the data and verified that there had been no instances of manual over-rides.

Concord concluded two major causes as follows:

- Although most of the DGPS base stations were completely wide open, several of them were not located ideally because of surrounding obstructions. Although surveyed accurately by static surveys, their RTK corrections were less than satisfactory as satellite geometry changed. For a few critical minutes, all rover observations were wrong because the reference station's RTK corrections were wrong.
- The rovers were always initialized in the most open area that could be found, then moved into survey points with obstructions. Conditions were such that results were not always reliable. Their solution for preventing such problems in the future is to double-check every initialization, regardless of the conditions.

NGS is aware that guidelines for RTK surveys needs to be published to cover situations such as this. As a "rule of thumb," redundant operations are necessary for almost every form of GPS surveying.

4.3.3 Highway/Bridge Construction

Reported by:
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Purpose

To establish the primary horizontal and vertical control points for all phases of the design and construction of proposed bypasses on Highway U.S. 70 at Goldsboro and Havelock, NC, including photogrammetric control, engineering surveys, right-of-way surveys, design surveys, digital terrain models (DTMs), construction layout, etc.

Accuracy and Cost Comparisons

For 71 control points at Goldsboro and 24 control points at Havelock, rapid static procedures (6-10 minutes per point), 15^{o} elevation mask, 5 second observation rate, and baseline lengths <5 km were used. Second Order Class 1 levels were run between 19 selected points:

- For Goldsboro, using two base stations and two rovers, the maximum difference between GPS- and leveling-derived heights was 9 mm. The average cost per GPS point was $318.
- For Havelock, using one base station and two rovers, the maximum difference between GPS- and leveling-derived heights was 2.4 cm. The average cost per GPS point was $328.

Lessons Learned

The method used in Goldsboro yielded higher accuracy. The method of operating two base units and two rover units simultaneously (a total of four receivers) proved to be very productive. This method allowed:

(1) Long observation times between base units (known monuments)

(2) Observation of two vectors to each new point from the different base units

(3) Observation of vectors between rover points (typically set as "pairs") -- all concurrently.

Thus the elevation differences between monument pairs at Goldsboro were significantly better than for Havelock.

Highlights

For two similar projects, the use of <u>two</u> GPS base stations with the rovers reduced maximum elevation errors from over 2-cm to less than 1-cm, compared with leveling, at no increase in average cost per point surveyed.

4.4 Four-Dimensional Elevation Surveys (x,y,z and time)

4.4.1 Crustal Motion Monitoring

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Purpose

To test the possibility of developing NAVD 88 orthometric heights for Southern California Integrated GPS Network (SCIGN) stations to support 4-dimensional (x,y,z and time) crustal motion monitoring in the state. The project had three targeted goals:

- To test the ability to develop GPS-derived heights over long distances
- To distribute coordinate and elevation data with regional coverage for further testing on local projects
- To test the capability of commercial GPS software.

Background

The SCIGN includes 45 existing stations, 45 stations in construction, and 250 sites funded. The GPS infrastructure in California also includes 10 Continuously Operating Reference Station (CORS) sites, 28 existing BARD (Bay Area Regional Deformation) sites, 20 Dense GPS Geodetic Array (DGGA) sites, and 18 Permanent GPS Geodetic Array (PGGA) sites.

Highlights

Leveling would have required 32,000 man-hours of survey effort, compared with 150 hours for GPS surveys, a savings of 99%. However, a slope of -0.23 parts per million (ppm) south and –0.39 ppm east was inferred from the data, indicating unmodeled slope in the geoid, bias in the datum, or undetected errors with the GPS receiver.

GPS baselines less than 50 km had rms elevation errors less than 1 cm. Baselines between 50 and 100 km had rms errors of 2.2 cm. Baselines longer than 100 km had rms errors of 3.2 cm.

Accuracy and Cost Analysis

The project met its goal of decimeter heights over a regional CORS network. Out of the eight check points, only one, at 13-cm, exceeded the target. Examination of the Los Angeles and Orange County stations, where baseline lengths are less than 50 km, shows a standard deviation of 9 mm.

A slope of -0.23 parts per million (ppm) south and -0.39 ppm east can be inferred from the data, indicating unmodeled slope in the geoid, or a bias in the GPS datum, or undetected noise in the GPS vectors.

Horizontal components for all GPS vectors under 100 km were repeatable at the sub-centimeter level, and compared similarly with NGS coordinates computed in 1995 and 1996.

Examination of height differences from repeat vectors showed good agreement (2.2 cm RMS) for lines under 100 km. Noise for lines over 100 km increased to 3.2 cm.

Because of the long distances involved, comparable leveling would have required an estimated 32,000 staff hours of survey effort, compared with 150 hours for the GPS observations, processing and analyses.

Lessons Learned

California's established GPS infrastructure of high-precision geodetic data and processing capacity offers a viable approach to the organization and maintenance of a statewide four-dimensional spatial reference system founded upon the CORS network. GPS data from the CORS, SCIGN, and BARD networks have been routinely used for horizontal control. This project demonstrated the feasibility to use commercial software and equipment, together with a CORS array, to maintain a vertical reference frame also.

4.5 Subsidence Monitoring

4.5.1 Long Beach GPS Subsidence Network

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Purpose

To design a high-precision GPS program to replicate the existing leveling program for monitoring subsidence in the region of the Wilmington Oil Field for the Port and City of Long Beach, California. The established precise leveling program, with estimated accuracy of 6 mm, includes a semi-annual network of First and Second Order leveling which has spanned a period of over 30 years. An interim target was set to obtain GPS-derived orthometric heights within one centimeter relative to the established Mean Lower Low Water (MLLW) datum at the Port.

Accuracy and Cost Comparisons

The GPS standard deviations of network adjustment residuals were 4mm horizontal and 7mm vertical. The GPS vertical standard deviation, compared with leveling heights, was 6 mm.

In one case, an error of 3 cm in the leveling data was discovered by the GPS networks. This occurred with one of the longer water crossings required to reach Oil Island Freeman. This 3-cm error was immediately suspect from the GPS data and subsequently proven in the next leveling campaign.

Highlights:

For less than 1/4th the cost of leveling, GPS surveys yielded comparable or higher accuracy.

Comparison between the cost of the leveling network and the GPS network is presented in Table 9. The leveling network includes a high number of benchmark stations, which distorts comparison of the cost per point.

	Leveling Network	GPS Network
Number of Network Points	**317**	**33**
Cost per Point	**$442**	**$1,030**
Data Collection	**1800 staff hours**	**330 staff hours**
Data Processing	**100 staff hours**	**85 staff hours**
Total Cost	**$140,000**	**$34,000**

Table 9.Cost Comparison Leveling vs GPS

Lessons Learned

This project demonstrated that sub-centimeter vertical motion and one-centimeter orthometric heights could be determined from a high-precision GPS network covering a limited area, i.e., 50 km^2 and 2.8 km average baseline length, when the geoid model is accurate and NGS' 2-cm guidelines for ellipsoid heights are followed.

4.5.2 Outside Canal and the Delta-Mendota Canal Subsidence Network

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Purpose

The purpose of this on-going project is to develop and use the most cost-effective means for monitoring subsidence activity along approximately 54 miles along the Delta-Mendota Canal, and 52 miles along the Outside Canals, in California's Central Valley, which deliver vital irrigation water supplies. This area experienced subsidence of over 26 feet between 1926 and 1970. This subsidence is mostly a result of ground water extraction and has been controlled since 1970, but with moderate and general subsidence continuing. Since the average gradient of the canal is only 0.4 feet per mile, even mild amounts of subsidence could be disastrous to this system. In fact, these canals have at times failed or been rendered useless as a result of subsidence.

Accuracy and Cost Comparisons

Assuming a single base station (monument 8694) as stable and fixed, 1996 GPS surveys (to NGS 5-cm guidelines) for 11 other stations, and the 1996 precise geodetic levels, were run through existing benchmarks along the entire 106 mile route. The maximum height differences, when compared to the 1997 GPS survey was 4.9-cm. However, results were confusing because the northern area indicated uplift when relative stability was evident. The single vertical base station 8694 was later determined to have subsided by 3-cm, through GPS surveys from CORS stations. This explained the apparent and illogical uplift of some stations relative to station 8694 when it was assumed fixed.

Leveling costs are essentially distance-based, whereas GPS costs are essentially point-based. If numerous heights along a level line are required, leveling is the more cost effective. However, if heights are required only at widely dispersed points, GPS may be more cost-effective.

- For a fee of $26,900, the 1997 GPS observations of 82 stations cost $328 per station.

- For a fee of $49,200, Second Order Class Two leveling was performed for 201 kilometers. The leveling cost $245 per kilometer, and the price would change very little, whether there were hundreds of stations enroute, or one at either end of the line. Therefore, if 82 stations would suffice for the project, GPS would be the more cost-effective method since the average cost per station would be $600 for leveling.
- At $328 per station with GPS, and $600 per station for leveling, GPS yields savings of approximately 45%.

Lessons Learned

When performing subsidence or crustal motion monitoring surveys, it is essential to have a stable, stationary mark on which to base the survey. Without a stable mark, the resulting values are inaccurate and confusing, and there is no way to tell what is really happening. This project re-iterates the need for more than one stable mark. While this is not an absolute requirement, without a second mark, there is no check on the first.

Figure 14 Subsidence Monitoring Along an Irrigation Channel

CORS sites are a viable alternative to local stable marks. CORS sites, in fact, appear to be ideal reference marks as they are clearly outside the local deformation area. To produce the same type of absolute deformation results with leveling would be prohibitively expensive. If a stable mark could be found within 100 kilometers of the project site, leveling to the mark could cost in excess of $24,500 based on the previously determined cost per kilometer. This cost per kilometer is also based on leveling across flat terrain, while the nearest absolute stable mark would likely be in the bedrock of nearby coastal mountains. As leveling is much more expensive in hilly terrain, this number of $24,500 could very easily be doubled by the time the leveling is done. Meanwhile, using GPS methods at the 5-cm level, references can be made to CORS sites simply by processing the project base station data, which is a necessary portion of the project, with the CORS site data. Therefore, with no additional fieldwork, ties to stable CORS site marks have been made with relatively little additional cost.

Conclusion

GPS vertical surveys are a viable alternative to leveling for subsidence monitoring under the right circumstances. For most applications, GPS is considerably less accurate than leveling; however, many projects do not require the high accuracy of precise geodetic leveling. In addition, GPS allows one to perform subsidence monitoring in areas where there are no stable marks without performing extensive leveling by allowing one to reference the survey to CORS sites. CORS sites could also be used to bring control to the perimeter of a leveling based subsidence-monitoring project, thereby eliminating the long, expensive run to control, but preserving the relative accuracy on site.

Highlights;

For subsidence monitoring, leveling indicated apparent and illogical uplift in points relative to a benchmark erroneously assumed to be stable. GPS 3-D surveys from distant CORS determined the "stable" benchmark had subsided by 3-cm, causing false conclusions as to relative uplift and subsidence.

At $328 per station for GPS, savings were approximately 45% when compared with $600 per station for leveling.

4.5.3 Unstable Dike Monitoring

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Purpose

To monitor (monthly) the 3-D coordinates of 24 points on an unstable dike, during construction to increase the height, width, and stability of the berm on Eagle Island, Brunswick County, NC.

Accuracy and Cost Comparisons

- Because surveys are performed monthly, McKim & Creed have had the opportunity to compare the costs for surveying the same points by different methods:

Elevation Survey Method	Cost for 24 Points	Cost per Point
DGPS Static Surveys	$6,000	$250
Leveling	$4,500	$187.50
Combined GPS and Leveling	$2,500	$104
DGPS RTK Surveys w/2 Base Stations	$1,500	$62.50

- Compared with leveling, all methods delivered vertical accuracy of 2-cm or better.

Highlights:

At $62.50 per point, GPS savings are 66% compared with $187.50 per point for leveling.

GPS is excellent for determining elevation changes over time. Furthermore, when the GPS rover can toggle between DGPS base stations, the use of two GPS base stations, simultaneously transmitting RTK corrections on different frequencies, can be a cost effective means for obtaining redundant observations. Care must still be taken to avoid multipath errors at the rover.

Lessons Learned

If points are very close together, then static GPS observations cost more than leveling. However, GPS RTK observations produced accurate results with savings of 66% compared with leveling.

If performing a large job with many points, or if the points are far apart or hard to get to, McKim & Creed learned that it would be more cost effective to use two base stations simultaneously, transmitting RTK corrections on different frequencies from different known points. The Leica 9500 series GPS receivers have a function in the controller that lets the rover unit toggle between base station frequencies. With this feature, the rover can collect redundant sets of coordinates on a point without having to make a return trip to that point as required by NGS guidelines.

RTK procedures were adequate to determine that points "C" and "D" at station 102+00 moved south approximately 0.3 ft. between November 1997 and January 1998, but remained stable between January and February.

4.5.4 Geodetic Control Surveys (1992 and 1998), Escondido, California

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Purpose

To provide control for aerial photogrammetric mapping of a 34 square mile area, and to establish 326 control monuments on a one-half mile grid throughout the city. The ultimate goal is to build a spatial inventory and descriptive record of each sewer line, manhole, water line, and gate valve itemized in a GIS database; this would allow rapid location in an emergency, and routine maintenance could be monitored, scheduled, and reported by querying the computer.

Accuracy Requirements

The city specified First Order Horizontal Control to be spaced at a three-kilometer interval, Second Order Horizontal Control to be a one-kilometer interval, and Third Order Vertical Control on all monuments

Procedures

In 1992, Manitou performed the survey measurements with single frequency GPS receivers. The First Order Primary Network was constrained horizontally to five State of California High-Precision Geodetic Network (CA-HPGN) control stations and vertically to 14 local benchmarks (2^{nd} and 3^{rd} order). The Second Order, Class 1, GPS Network was horizontally tied and constrained to the entire thirty-one (31) stations in the First Order Primary Network, and they were vertically tied and constrained to the fourteen (14) local bench marks cited, plus an additional 38 local bench marks. Level circuits and reciprocal trigonometric levels were run through selected GPS stations from the existing benchmarks.

In 1998, Manitou re-observed key tie points with dual frequency GPS receivers.

Results

The final 1992 base line results indicated that 99.6% of the 23,511 base lines were better than 20 ppm precision ratio for Second Order, Class 1 (1:50,000), and 98% were better than 10 ppm precision ratio for First Order (1:100,000). Of the 326 stations, the error ellipse ranges were as follows:

- Horizontal: 279 stations between 0.00 and 0.10 feet; 47 between 0.10 and 0.20 feet.
- Vertical: 294 stations between 0.00 and 0.10 feet; 30 between 0.10 and 0.20 feet; and 2 (HPGN's) between 0.20 and 0.30 feet.

Costs

- The preliminary layout of the one-kilometer control network and client coordination cost $5,000 ($15.34 per point).
- The monument recovery, installation of new monuments, and setting aerial targets (including supplies and jackhammer and air drill rental) cost $20,000 ($61.35 per point).
- The GPS planning and observation (including amortization of the GPS receivers) cost $64,000 ($196.32 per point)
- The data processing, including downloading receivers, processing baseline vectors, running loop closures, adjusting the first order and second order networks, and report preparation, cost $24,000 ($73.62 per point.
- The total cost per point, excluding setting new monuments and recovering existing monuments was $285.28 per point.

1992 Lessons Learned

In preparing the original task list and estimate of time, the session planning time was grossly underestimated. The preparation of sky chart with the site obstructions included greatly decreased the number of missed sessions due to loss of the required number of satellites. However, this increased planning, while well worth the time, increased the estimated session planning by fifty percent.

The volume of paper was staggering. With monument recovery card session planning logs, station observation logs and maps of the observation routes for each receiver for each day, the data filled twelve 1.5-inch thick three-ring binders. Efforts were made to sort all the sheets that would be reused for subsequent observations at the same monuments, but more time and emphasis on this task was necessary.

The amount of organization required to keep supplies on hand for the monument installation crew and the design and time allocation for the daily observations and move times kept two people, instead of one as planned, occupied full time.

Fixed height antennae poles should be used in the future to eliminate the possibility of human error.

The single-frequency receivers produced the required accuracies within the mapping area where the maximum vector length did not exceed 6 km. However, dual-frequency receivers would allow reduced observation times and improved vertical precision. The vertical component of the network ties (12 km to 28 km in length) could not be included in the adjustment because of the excessive error introduced when they were set to fixed.

1998 Re-Observations

Highlights:

Single frequency GPS receivers, used in 1992, satisfied vertical accuracy requirements only where maximum base lines did not exceed 6 km. Dual frequency GPS receivers, used in 1998, allowed longer baselines (12 to 28 km) to be included in the network adjustment

The ties to the Countywide Network and the ties to station 1010 in the Escondido Project were re-observed in March of 1998. The re-observations were made with Trimble dual frequency GPS receivers in accordance with NGS standards for GPS elevation surveys at the 5cm level. Manitou obtained NAVD 88 elevations on stations Lomax, SDGPS 03, SDGPS 32, and SDGPS 34 from CALTRANS. The horizontal vectors fit within millimeters of the record vectors, indicating there had not been any differential crustal movement between these stations. The plot of earthquake faults for the local area indicates a swarm of faults east of the Cuyamaca Mountains in the Anza Borrego Desert and additional faults in the vicinity of San Diego Bay.

The Horizontal Time Dependent Program developed by NGS reveals approximately 16 cm (0.52') of secular movement between the 1991.35 station coordinates and the 1995 station coordinate for the permanent tracker at station Monument Peak. This difference in position is the distance the Pacific Plate has moved in relation to the North American Plate in the years between 1991 and 1995. The vertical movement is separate and distinct from the lateral movement. The vertical movement is predominant in areas of ground water, oil, or natural gas extraction. The Northridge earthquake was both a lateral and a vertical movement, and different from the slow steady creep characteristics of the secular movement.

Geoid 90 was the gravity model in use when the observations were conducted in 1992. Comparisons with heights obtained from CALTRANS and the Geoid 96 differences show excellent correlation. The difference in the orthometric height from 1992 to 1998 indicates approximately 0.65-meter bias. The Geoid separation from David Zilkoski's unpublished special study for San Diego County indicates a reasonably consistent bias from the Geoid 96 separations. The correlation of the CALTRANS leveled orthometric heights with the heights obtained from the GPS measured ellipsoid heights and the Geoid 96 separations indicates Geoid 96 fits this portion of San Diego County quite accurately. The dual-frequency receivers provided the increased vertical accuracy, compared to the single-frequency receivers, which allowed the network ties (12 km to 28 km in length) to be included in the vertical constraints for the 1992 network adjustment.

Based on these test results, the Escondido project could be reprocessed to derive NAVD 88 orthometric heights at the 5-cm accuracy level.

4.6 GPS Control Surveys

4.6.1 Baltimore County, Maryland

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Purpose

The primary objective of the county's GPS-leveling project was to support the overall GIS mission of the county directed to modernize the information infrastructure. The secondary objective was to investigate the practical feasibility of GPS procedures to support georeferencing of GIS via high-precision airborne GPS-supported aerial triangulation, and to study cost and time efficiency of the technique. The tertiary objective was to see how far GPS could be used for establishment of vertical control bench marks for other surveying and developmental engineering projects in the county.

Background

Baltimore County enterprise GIS has been, from the beginning, a unique project relying on the integration of a number of state-of-the-art geodetic and photogrammetric concepts and techniques for the development of high precision geo-data. The establishment of a geodetic control network, employing the NGS defined specifications for GPS-derived elevations, is a classical example of this approach. Consequently, this project is representative of the first large scale planned GIS development effort at the local government level in the U.S., to successfully integrate NGS specifications and procedures of GPS techniques for vertical control, substituting for conventional leveling.

The GPS 3-D surveys were planned to provide vertical accuracy at a 2 cm level. The County worked closely on this project with NGS to ensure the National Spatial Data Infrastructure (NSDI) framework. This partnership proved invaluable for the experiments with seashore height model use for airborne GPS, and pioneering GPS technique application in GIS, which made a three dimensional GPS control network a reality.

Project Phases

The basic approach for geodetic control was to establish a sparse horizontal GPS framework of control covering the entire county in phase 1 of the GIS project. The density of monuments was planned at a distance of about six to seven miles apart. The county’s minimum homogenous geodetic control network strategy was to have limited coverage for economic reasons to be subsequently densified on a need basis. The network, comprised of 52 GPS points covering the entire county area of 675 square miles, included 26 points in phase 1, covering about 125 square miles. Additionally, 25 vertical benchmarks were established by leveling in phase 1 to support photogrammetry and development projects, and for establishing a geodetic reference framework.

In phase 2, the strategy was based on a combination of leveling and GPS surveys. A few ground control points were connected by short leveling loops from nearby existing benchmarks. The remaining control, particularly in difficult hilly and riverine terrain, or where existing vertical control was sparse, was planned using GPS techniques as pilot experience. If the method proved successful, phase 3 work was to be undertaken with the new procedure. This approach proved beneficial, as only 33 more new GPS monuments were added in phase 2 and 3 for multi-purpose use.

Phase 1 and Phase 2

In phase 2, four GPS baselines did not meet the guideline's 2-cm tolerance limits. All of these baselines were greater than 10 km, which exceeds the maximum length requirement stated in NGS' guidelines. This indicates that the NGS requirement to limit the length between base lines to 10 km has validity. Several baselines were re-observed, with different satellite geometry, and the results did satisfy the 2-cm tolerance.

Phase 3

The primary objective of phase 3 GPS surveys was to provide 3-D positioning of minimum essential ground control to support airborne GPS supported photo triangulation. The secondary objective was to provide additional minimum essential densification of control at spacing of about 6 km throughout the 290 square mile area.

A few of the GPS derived elevations were outside the 2-cm accuracy threshold, but they tended to be on the periphery of the project area or outside it. As such, they did not significantly contribute to inducing error in the adjusted 3-D positions of the other interior stations. The results satisfy requirements of 2 cm level accuracy in this project.

Conclusions

Until recently, reliable vertical bench mark values sufficient to support high accuracy photogrammetric projects, GIS data bases, geodetic control, and a variety of surveying and engineering project applications could only be obtained by leveling. While providing good results, leveling is extremely time and labor intensive, and causes delays and higher costs for survey work. Baltimore County's GPS pilot project in Phase 2 as well as Phase 3 production fully met the expectations of achieving 2-cm orthometric height accuracy. Even a slightly relaxed accuracy level of 2-cm to 4-cm should be sufficient to support the high accuracy GIS photogrammetry specifications of this and many other similar projects. The experience of this project validated the NGS guidelines and procedures for obtaining reliable GPS heights, usable for many engineering and surveying applications.

Cost Comparisons

The County accomplished significant cost savings of about 80% compared with the conventional method of leveling in the final Phase 3 of the project. The time efficiency was also remarkable, which was about 10 times more efficient in Phase 3 as compared to Phase 1 of the project.

> **Highlights:**
>
> **Compared with conventional 3-D survey control, GPS provided cost savings of 80%. Some GPS control surveys were completed in 1/10th the time of prior**

- Phase 1. The cost of leveling for Z, and GPS surveys for X and Y, cost $600 per square mile.
- Phase 2. The cost of some leveling for Z, and some GPS surveys for X, Y, and Z cost $358 per square mile
- Phase 3. The cost of 3-D GPS surveys for X, Y, and Z cost $104 per square mile.

4.6.2 Eastside Reservoir Project (RTK Surveys)

Reported by:
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Purpose

Initially, the purpose of the project was to use GPS to provide control of photogrammetric mapping for construction planning, earthwork monitoring, and volumetric computations. Ultimately, the purpose was to use GPS RTK procedures to provide real-time monitoring and volumetric computations for this major construction project.

Background

When the Eastside Reservoir is built by the end of 1999, at an estimated cost of $1.9 billion, it will be one of the largest water reservoirs in the world. It will be formed by two earth/rock filled dams 4.5 miles apart, plus a third earth/rock filled dam at the low point in the north rim. It will have a storage capacity of 269 billion gallons, cover an area of 4,500 acres, and have a varying depth of 160 to 260 feet. The West Dam will be the largest earth/rock dam in the United States, 8,700 feet long and 285 feet high. It will have 9,000 acres set aside for wildlife reserves to protect and enhance the region's wildlife and plants. In addition, another 1,950 acres of recreational and open space areas are being planned for camping, hiking, picnicking, riding, fishing, and boating in special lakes separated from the main reservoir.

The Metropolitan Water District of Southern California (MWD) is building this capital improvement project in support of the expected growth in the Southern California area. This reservoir will double the amount of surface storage available for MWD's service areas and ensure a more reliable delivery of water during peak summer months, droughts, and emergencies. This enlarged water capacity will protect both the quality of life as well as the economy from water shortages that have plagued other parts of the West.

Approach

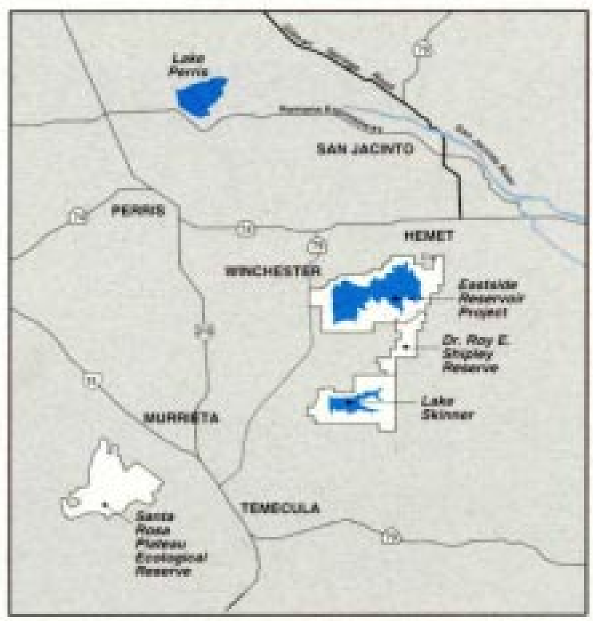

Figure 15 Eastside Reservoir Project

MWD contracted Psomas and Associates to provide survey personnel as an extension of their survey staff for this five-year project. At the height of the construction period, the reservoir will employ over 500 construction workers, including construction managers, engineers, surveyors and archaeologists. The survey staff plays an important part in maintaining a tight schedule during the excavation and placement of some 90 million cubic yards of clay, sand, and rock to build the dams.

At the outset of the project, it was decided to divide the 9,000 acres into 1,000-foot square grids and calculate the quantities by aerial photogrammetric mapping. For this purpose, the surveyors set permanent monuments and placed aerial targets at selected locations. Where possible, these monuments and targets were placed at secure areas outside construction activity. All survey control was established using GPS techniques by ties to a primary control network established by the

MWD before construction. At the beginning of the project, aerial photos were obtained for the entire project area. This procedure would be repeated at regular intervals throughout the project. For calculation and reporting of construction quantities, it was planned that aerial photos for specific areas would be completed as needed.

From the project beginning, the surveyors used GPS surveys, including RTK, to carry out field surveys. A semi-permanent, continuous operating reference station (CORS) was maintained to provide differential correction for all field observations for the first year of construction. MWD replaced this station with two permanent CORS at the east and west ends of the project. These CORS were constructed by installing pilasters with antennae and power lines for electrical power. These reference stations will remain as an integral part of a dam deformation system to monitor dam performance.

Photogrammetric Mapping of 400 Acres

Function	Labor	Costs	Time
Setting of aerial control targets	**4 man days**	**$2,600**	**2 days**
Aerial photography		**$500**	**1 day**
Stereo plotting and mapping	**116 man days**	**$50,000**	**58 days**
Digital map overlay for quantities	**1 man day**	**$800**	**1 day**
Total	**10 man days**	**$53,900.00**	**64 days**

Table10. Eastside Reservoir Photogrammteric Mapping Costs

MWD's original plan for using aerial photogrammetric mapping for quantities was soon replaced by using RTK surveys to obtain the needed quantities in real time. This method soon became the preferred method for obtaining all on-site quantities. Table 11 shows the 71% savings achieved by using GPS.

RTK GPS Surveys of 400 Acres

Function	Labor	Costs	Time
RTK-GPS survey of site	**19 man days**	**$12,920**	**1 day**
Office transfer of GPS data to PC	**0.5 man days**	**$550**	**1 day**
Preparation of digital model	**1 man day**	**$1,100**	**1 day**
Digital map overlay for quantities	**1 man day**	**$1,100**	**1 day**
Total	**4.5 man days**	**$15,670.00**	**4 days**

Table 11. Eastside Reservoir GPS RTK Mapping Costs

The RTK surveys were carried out by vehicle-mounted GPS and personal-mounted GPS and walking. The vehicle-mounted GPS was mounted in a vehicle, with a known antenna height, and measurements were taken while the vehicle was moving. At cost savings of 71%, GPS accuracy exceeded those of the photogrammetric mapping.

Findings

- Providing quantities by mapping has proven to be a very time consuming and costly method of reporting. Prior to the flight, surveyors will inspect all aerial targets for the subject grid block and replace and survey all targets found missing. After the sight is ready, the aerial contractor obtains the pictures and compiles mapping. Timing of the aerial flight is dependent on the weather conditions and can be delayed by days, or by weeks. Final quantities are available to the construction manager team 30 to 60 days after request.

- Using RTK techniques, the surveyors are able to complete a multiple number of grid blocks on a daily basis, and the office surveyor can process the data immediately for reporting. Using a number of roving GPS receivers operated by only one surveyor each, large areas can be completed within a few days. When the surveyors are working near moving heavy construction equipment, there are times when a second pair of eyes is needed to provide protection.

- Use of RTK has provided a means for visual inspection of wide areas by the surveyors. The surveyors have found small culverts, wells, pipes, and other small important features that are not visible when compiling mapping from aerial photographs. This visual inspection and collection of data can provide a means to log data for historical records. It is possible that these records and data files collected by the surveyors can be used for collection of evidence or recovery of facts in some future case.

- Accuracy of RTK surveys have been found to be very reliable. At the outset of the project, when some RTK positions were obtained without a local geoidal model, the heights were subject to errors from 2 cm to 10 cm in areas. After modeling the local geoid, the heights were found to be within 1-cm range. This was approximately 2.5 times better than height obtained from aerial mapping.

- The level of effort associated with obtaining quantity volumes by survey methods is considerably less then using aerial mapping. This is evident from the cost of labor using prevailing wages for the trades. The MWD has analyzed costs associated with the two methods and has found that savings associated with survey methods exceed 200% of the costs associated with aerial mapping. This is a large saving considering these reports are needed on daily basis over a five-year period.

Conclusions

- Real-time kinematic (RTK) GPS surveys have been proven to be an efficient and cost effective means of collecting vertical data within a large construction site. Under most conditions, the cost savings are substantial over the use of aerial photography for data collection.

Highlights:

GPS RTK mapping cost savings were 71% compared with photogrammetric mapping, and GPS required less than 10% the time.

On-site DGPS CORS were instrumental in project success.

- The use of GPS requires a reliable height reference system within the project area. Establishment of this reference system can be costly at the start of the project if there are conflicts in or lack of vertical benchmarks. For this project, the MWD had to run miles of levels from known vertical control into the site. Using GPS for this initial leveling would have saved considerable time and money.

- The use of RTK GPS surveys becomes very cost-effective when permanent CORS are established at the inception of the project and a good geoidal model is in place.

- GPS survey techniques have provided a reliable tool to the surveyors and construction managers to collect data. With additional development and refining, it is possible to collect these data in real-time, with a direct radio link to a central database. This will further increase the efficiency of the construction industry and provide an edge in the competitive world market.

4.6.3 Geodetic Control Network, City of San Jose, California

Reported by:
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Purpose

To establish a city-wide geodetic quality control network, following NGS 2-cm guidelines, to be used as base control for subsequent surveys by City of San Jose personnel and private consultants, and to support the city's GIS/LIS base map development.

Accuracy and Cost Comparisons

After the GPS network was constrained horizontally and the level line was adjusted, differences in orthometric heights were found to be consistently less than 1 cm.

The cost to establish horizontal coordinates and GPS derived orthometric heights on 111 monuments (including 8 primary control points), prepare a report, and file a 9 page Record of Survey of the results with the County Recorder, was $500.00 per station. The cost to establish NAVD 88 orthometric heights only (no horizontal coordinates) by leveling on 68 benchmarks was $420.00 per point.

In February 1998, six base lines between 9 GPS/benchmark monuments were re-observed by both methods, with differences between unadjusted level runs (NAVD 88) and a free adjustment of the GPS observations based on GEOID96 of 0.0003, 0.0095, 0.0017, 0.0019, 0.0070, and 0.0200 meters (2-cm maximum discrepancy). "It took twice the time to run the levels as it did to observe the base lines by GPS. In these times of tight budgets and shrinking funding, it becomes apparent that a considerable amount of money can be saved by utilizing a properly designed GPS network to establish elevations for most engineering projects."

Lessons Learned

With today's technology, electronic digital levels, computers, software packages, and other labor saving devices, it still takes a minimum of a three-person crew to economically run a level loop that meets FGCS Second Order Class 1 Specifications. On this subject project, we were able to complete approximately 4.9 miles per day. On the other hand, the same three people, using dual frequency GPS receivers with field techniques that meet accepted guidelines and specifications can obtain elevations on nine (9) bench marks that are about 1 mile apart (8 miles total) in one working day. The elevations derived from these GPS observations easily duplicate those elevation results obtained from leveling.

One of the main lessons we have learned from this project is that if enough bench marks with properly determined elevations are used to model a GPS network or line of stations to be used as bench marks, the output of GPS versus leveling can be almost doubled by using GPS methods, without sacrificing any accuracy in the result.

Highlight:

Productivity can be almost doubled by using GPS in lieu of leveling.

4.6.4 Geodetic Control Network, Davidson County, North Carolina

Reported by:
Webb A. Morgan
Webb A. Morgan & Associates, P.A.
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Purpose

To establish horizontal and vertical control adequate to perform aerial triangulation computations to develop digital orthophotos and a planimetric base map for Davidson County's GIS; and to provide additional control stations to be used by local engineers and surveyors for maintaining the county's GIS.

Accuracy and Cost Comparisons

All basic vertical control was extended from existing NGS, NCGS, or NC DOT benchmarks and referenced to NAVD 88. NGS' 5-cm Guidelines for GPS Elevation Surveys were followed, and Geoid 96 was used to compute orthometric heights. NGS' VERTCON was used to convert NGVD 29 to NAVD 88 orthometric heights.

There were a total of 96 primary control marks determined for this project. The average cost per station was $800.00. This included field reconnaissance, visibility sketch, placement of monuments, mission planning, data acquisition, and computations.

Lessons Learned

GPS is a practical and cost-effective alternative to leveling for large project areas where vertical accuracy requirements do not exceed the 5-cm vertical positional tolerance. The final result of the Davidson County survey far exceeded the photogrammetric control accuracy requirements. The accuracy of the geoid model furnished by NGS has a major impact on the accuracy of the resultant orthometric heights.

Highlights:

GPS is a practical and cost-effective alternative to leveling for large project areas. The results far exceeded accuracy requirements for photogrammetric control.

4.6.5 GPS Control Surveys, Brunswick and Bladen Counties, North Carolina

Reported by:
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McKim & Creed Engineers
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Purpose

To establish three pairs of horizontal and vertical control points for Magnolia Green Golf Community, and to establish horizontal and vertical control for replacement of Bryant Neil Pond Bridge #46 on NC 131.

Accuracy and Cost Comparison

- The golf community DGPS static surveys cost $1,500 per 6 points or $250 per point; conventional surveys cost $2,040 per 6 points or $340 per point. Thus, GPS status surveys were performed at cost savings of 26% compared with leveling. The difference between GPS derived elevations and leveling varied between 2 mm and 1.3 cm.

- The bridge DGPS static surveys cost $1,362 per 5 points or $272 per point. Using conventional traversing methods would not have been practical for this project because the existing NCGS monuments were too far from the project area. McKim & Creed did compare leveling between the new GPS points, and the GPS elevation differences agreed with leveling differences within 2 mm.

Lessons Learned

From the golf community project, McKim & Creed learned the importance of extensive mission planning and control point location to optimize the project control. As a result, none of the GPS control points were lost as a result of construction activity. They also learned that more than two GPS receivers are needed to efficiently perform a static survey; they learned that four GPS units appear to give the most value on a per-point basis.

Highlights:

At $250 per point for GPS static surveys, GPS yielded savings of 26% compared with the $340 per point costs of leveling.

Conventional surveys would have been impractical because of the long distances from existing NCGS survey control. Elevations were accurate between 0.2 and 1.3-cm.

From the bridge project, McKim & Creed learned that it needed to incorporate as many "known" vertical monuments as possible in order to refine the geoidal model. Otherwise, elevation differences would have been larger than 2 mm.

5 – TIME & COST COMPARISONS

The projects described in this chapter were performed in accordance with NGS' (November 1997) guidelines for elevation surveys at the 2-cm accuracy level for ellipsoid heights, referenced previously.

5.1 Background

Purpose:

- **To compare leveling and GPS vertical surveys (with Geoid 96) for determining NAVD 88 orthometric heights**
- **To evaluate relative differences in the accuracies, time, costs, and other variables**

As part of the National Height Modernization Study, NGS compared leveling with GPS vertical surveys (using Geoid96) for determining NAVD 88 orthometric heights; and evaluated relative differences in accuracy, time, costs, and other variables. Comparisons were performed in portions of California and North Carolina that have had difficulty with subsidence, crustal motion, and/or areas with large uncertainties in the geoid model due to the lack of data. Survey logbooks, and raw and processed GPS digital files were provided to NGS for accuracy comparisons. Time and cost data were also provided for comparison.

Proposals were solicited from leading survey firms in California. Cross Land Surveying, Inc. of San Jose, California, and Johnson - Frank & Associates, Inc. of Anaheim, California, were chosen to survey two test areas selected by Don D'Onofrio, NGS' California State Advisor.

Both firms were assigned different project areas along the California aqueduct in Fresno County, west of the town of Mendota in California's Central Valley. Cross Land Surveying, Inc. was assigned the southern project area, and Johnson - Frank & Associates, Inc. was assigned the northern project area. Both areas were approximately 30 kilometers in length. Both firms were tasked to survey specified monuments using two procedures:

(1) Leveling using modified Second-order, Class I, double-run procedures for 20 specified monuments at approximately 1-mile intervals

(2) GPS vertical surveys, using modified 2-cm guidelines, as detailed in the NOAA Technical Memorandum NOS NGS-58, dated November 1997, for 14 of the same monuments.

The purpose of these projects was to determine the relative differences in costs, accuracies, time, and other variables; therefore, certain cost-reduction compromises could be made that did not impact these relative comparisons. Specifically, the leveling modification enabled single-run modified double-simultaneous procedures to be used in certain circumstances in lieu of double-run level loops; and the GPS modification allowed GPS manufacturer's software to be used in lieu of NGS' OMNI software.

Cost savings were highly variable for the following reasons:

- The contract surveys confirmed the significant cost savings and desired accuracy level results found in the case studies, as well as the other additional benefits identified by the case studies. The cost savings are discussed in more detail below.

- In general, conventional surveying methods are more accurate than GPS methods for height determination over relatively short distances. However, at the 10 kilometer spacing recommended for the National Height System, GPS accuracies are comparable with those attained by conventional surveying for most applications.

- One of the surveys highlighted an additional benefit of utilizing GPS to determine heights. A difference in the results obtained by the two methods identified the need to refine the geoid model (used to convert GPS-determined heights to those determined by conventional methods) for the local area. This benefit will be realized for other areas if GPS methods are used to implement the National Height System

5.2 California Southern Project

Reported by:
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Cross Land Surveying, Inc., surveyed between benchmark PID GU4142 (Z1444), at aqueduct post mile 111.91, and benchmark PID GU1348 (D1262), at aqueduct post mile 131.7. The leveling was performed with a Wild NA2000 electronic digital level, two 3-meter invar bar-coded level rods, and two Wild turning trivets. Of the total leveling distance, 27.5 kilometers were surveyed with single-run leveling; and 9.6 kilometers (4.8 kilometers one way) were surveyed with double-run leveling. The GPS surveys were performed with four Trimble 4000 SSE dual frequency GPS receivers with L1/L2 geodetic antenna with ground planes.

5.2.1 Accuracy Comparisons

The unadjusted heights are based on starting the level run at Point No. 1348, with an elevation of 100.1877 meters, and running northwesterly to Point No. 4142, utilizing field observed data only. The GPS elevations are based upon a least squares adjustment utilizing Geoid 96 and holding the orthometric height of Point No. 1348 fixed at 100.1877 meters.

When utilizing the elevations from the "free" adjustment of the leveling data, which held the elevation of Point No. 1348 at 100.1877 meters, the following comparisons were made for the difference in orthometric heights between Point 1348 (southernmost point) and Point 4142 (northernmost point):

(1) Height difference = 2.35665 meters from NGS' 1989 unadjusted heights

(2) Height difference = 2.30296 meters from Cross' 1998 "free" adjustment of leveling

(3) Height difference = 2.2911 meters from Cross' 1998 raw unadjusted leveling heights (leveled heights with no adjustments whatsoever)

(4) Height difference = 2.2784 meters from Cross' 1998 "free" adjustment of GPS heights (Geoid 96)

The elevation of Point 1348 was assumed fixed at its 1989 elevation of 100.1877 meters, although it probably subsided between 1989 and 1998. In relative comparisons between leveling and GPS surveys, the following conclusions were reached:

- Comparison of (1) and (2) indicate that one of the two benchmarks subsided over 5-cm more than the other benchmark between 1989 and 1998.
- Comparison of (2) and (3) indicate the accuracy of the unadjusted raw level heights with regard to the minimally constrained height network.
- Comparison of (2) and (4) indicate potential orthometric height discrepancies of only 2.46 cm, over the 30 kilometer project, between 1998 leveling and GPS surveys.

The results proved that accuracies in the 2-cm range can be achieved, at the 95% confidence level, utilizing GPS procedures, provided the Geoid model accurately represents the geoid in this area. The accuracy of the Geoid model is both the controlling and the limiting factor.

5.2.2 Time and Cost Data

Survey Phase	Differential Leveling		GPS Leveling	
	Staff Hours	Costs	Staff Hours	Costs
Survey Planning – Labor	**6.5**	**$488**	**12.5**	**$938**
Deployment – Labor	**12 (4x3)**	**$1,050**	**12 (4x3)**	**$1,050**
Field Surveys – Labor	**316 (4x79)**	**$16,016**	**57 (4x13+5)**	**$4,379**
Survey Computations - Labor	**19**	**$1,425**	**16**	**$1,181**
Labor Subtotals	**353.5**	**$18,979**	**97.5**	**$7,548**
Other Direct Costs (ODCs)		**$2,661**		**$802**
Totals		**$21,640**		**$8,350**

Table 12. California (South) Time/Cost Comparisons

Since the same 4-person survey team deployed for both surveys (GPS and leveling), the 12 man-hour deployments were not actually duplicated.

5.3 California Northern Project

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Johnson-Frank & Associates, Inc.
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Johnson - Frank & Associates, Inc. surveyed between benchmarks PID GU4142 and PID GU0296. The leveling was performed with two Jena N1002 reversible compensator optical precision leveling systems. The GPS surveys were performed with five Trimble 4000 SSI/SSE dual frequency GPS receivers.

5.3.1 Accuracy Comparisons

The contract called for single run of the entire project and double run of any section that did not match the NGS 1989 leveling by 6mm times the square root of the kilometers run. As the survey progressed, only one or two sections in the entire project would close with the record, while all double run levels would close within 1 or 2 mm on themselves. After discussion with the NGS California Advisor, it was decided that if the GPS matched the leveling, that would be a sufficient check, as it was not the purpose of the project to determine the magnitude of subsidence problems in the area.

An unconstrained adjustment was made, holding only the most southeasterly benchmark elevation, GU4142/Z1444. Statistically, least squares indicates a standard error in the total 30-kilometer project of 7.4 mm. Holding only the most southeasterly benchmark, the survey missed the most northwesterly benchmark, GU0296/92.58R, by 2.7 cm, as determined by 1989 raw leveling. Second Order Class I specifications allow 3.3 cm in that distance. However, due to crustal movement, sectional misclosures with the 1989 NGS leveling at other bench marks along the run were varied up to a maximum of 22 cm.

All GPS data were downloaded and baselines processed, using the broadcast ephemeris, at the end of both days of GPS operation. After the second day's baselines were completed, a check was made to ensure that the height element of the first day's baselines matched those of the second day's by less than 2 cm, per the NGS guidelines. One line was found to have a 2.5cm split. This line was re-observed, and the height element of the re-observed baseline was right in between the first two.

The Precise Ephemeris was downloaded from the NGS web site, when available, and all GPS baselines were reprocessed. The resulting baselines were imported in StarPlus' StarNet, and an adjustment was run, holding only the most southeasterly benchmark and using Geoid 96 to produce orthometric heights. Statistically, the standard error in vertical for the 30 kilometers is 7.5 mm.

The orthometric height determined by GPS at the most northwesterly benchmark was 16.4 cm lower than the height determined at the same point using leveling. In reviewing the intermediate benchmarks, it was evident that the differences appeared to be on a slope from south to north, indicating a discrepancy between the height systems.

The heights derived from leveling, holding only the most southeasterly bench mark, were imported into StarNet, and held fixed to allow the software to compute a best fit tilt in the north and east axes. Once the geoid tilts were computed, the elevations were again set free except for the fixed benchmark at the southeasterly end. Using this computed tilt in the geoid, the GPS-derived orthometric heights then matched the leveling-derived orthometric heights to 1.2 cm or less in all locations.

Unlike the southern project, the orthometric heights derived from GPS differed from those derived from leveling by 16-cm. By using traditional leveling to help define and correct the local slope of the geoid, the orthometric heights derived from GPS matched leveled heights to 1.2-cm or less at all locations. As a side benefit, this project identified an inaccuracy in the geoid model in the project area. This serves as an example of how implementing the NHS plan nationwide will identify these types of differences in the geoid model and how they will be resolved and incorporated into the NHS.

5.3.2 Time and Cost Data

Survey Phase	Leveling		GPS	
	Staff Hours	Costs	Staff Hours	Costs
Survey Planning – Labor	**6 hr**	**$574**	**15.8 hr**	**$1,624**
Deployment – Labor	**27 hr**	**$2,183**	**29 hr**	**$2,708**
Field Surveys – Labor	**181.5 hr**	**$12,908**	**77 hr**	**$6,277**
Survey Computations - Labor	**23.5 hr**	**$2,018**	**17.8 hr**	**$1,695**
Labor Subtotals	**238 hr**	**$17,683**	**139.6 hr**	**$12,304**
Other Direct Costs (ODCs)		**$1,740**		**$2,073**
Totals		**$19,423**		**$14,377**

Table 13. California (North) Time/Cost Comparisons

Additional expenses were incurred by both survey firms for proposal and cost estimation, contract review and negotiations, administration, coordination with D&D and NGS, and report preparation.

5.4 North Carolina Project

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The North Carolina Geodetic Survey performed the NHMS project in the Asheville area of western North Carolina. The project extended from the downtown area of Asheville to the Eastern Continental Divide, which is approximately 20 miles east of Asheville. The leveling route was 60 kilometers in length. The average difference of elevation between sections was 14 meters, with the maximum difference being -54 meters. The section length average was 0.75 kilometers. The leveling was performed to Second Order Class I specifications. All new sections were double run. The leveling was performed with a Jena NI005A compensator optical precision leveling system with built-in micrometer and a Zeiss NI-2 compensator with an attached micrometer and four Kern GK-23E invar rods. NGS turning pins and thermistors were also used.

The GPS surveys were performed with four Trimble 4000SSE and two Trimble 4000SSI dual frequency GPS receivers with 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 were processed with GPSurvey (Version 2.3). The precise ephemeris was used to process the data. The adjustment of the GPS data was performed with the NGS adjustment program "ADJUST". Geoid96 was used to obtain geoid heights. NCGS followed the procedures outlined in "Guidelines to Establishing GPS-Derived Ellipsoid Heights" (Version 4.3, 2CM Standard).

5.4.1 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 bench marks 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 2-5 centimeter heights can be obtained at the 95% confidence level, utilizing proper field procedures and a good geoid model.

5.4.2 Time Comparison (GPS versus Leveling)

The time comparison did not include the staff hours for reconnaissance for the GPS or leveling phase. Mark recovery and mark setting is required to perform both GPS and leveling. The reconnaissance for GPS differs slightly, but statistically they are equal. Also, additional geodetic marks were recovered along the level route. Consistent with standard practice of the NCGS, additional marks along the level route were positioned vertically. Positioning these additional marks in the leveling phase did not affect the comparison of staff hours between geodetic leveling and the GPS observations.

Field Survey Phase (Staff hours)	Leveling (2nd Order Class I)	GPS (2cm Standard)
Field Observations	1,111	282
Computations	25	25
Totals	**1,136**	**307**

Table 14. North Carolina Geodetic Survey Time Comparisons

Using the time comparison above, the cost to perform the North Carolina project using geodetic leveling techniques would increase by 270% when compared with the cost of performing the project using GPS

5.4.3 Project Statistics

GPS Elevation Surveys

Total number of stations occupied = 39

Existing horizontal stations = 11

Existing vertical stations = 3

Existing horizontal/vertical stations = 12

GPS stations established = 13

Leveling

Total number of stations occupied = 81

Existing vertical stations = 41

New vertical stations = 40

5.5 Summary

The time and cost data for the three projects are summarized in Table 15.

	Leveling			GPS		
	Km	Time	Cost	Points	Time	Cost
S. Calif.	30	354	$21,640	14	97	$8,350
N. Calif.	30	238	$19,423	14	140	$14,377
North Carolina	60	1,136	Costs not Available	39	307	Costs not Available
Averages	**14.4 staff hours/km leveled**			**8.1 staff hours/GPS point**		
	$684/km leveled (flat terrain)			**$811/GPS point**		

Table 15 Statistics from Cost Comparison Projects

GPS costs averaged $811 per point. Leveling costs averaged $684 per kilometer. The leveling costs are very conservative, based on the two California projects in flat terrain.

Costs of GPS elevation surveys are estimated by the number of points surveyed. Within reason, distance is not a factor. With GPS, surveying a point 5 miles away costs very little more than surveying a point 2 miles away from the DGPS base station.

Relative to the other projects, the GPS costs were higher in the North California project because of unexpected discrepancies between orthometric heights derived by GPS compared with those from leveling.

Cross Land Surveying, Inc. costs averaged approximately $600 per GPS point, whereas Johnson-Frank, Inc. costs averaged over $1,000 per GPS point. Cross encountered no major difficulty with the Geoid 96 model in the southern area, whereas Geoid 96 appeared to inadequately represent the geoid in the northern area surveyed by Johnson-Frank & Associates. Subsequently, Johnson-Frank resurveyed some areas, extensively analyzed and remodeled the geoid from leveling, and incurred additional

GPS costs from equipment rental. These were the major reasons why their costs per GPS point were higher.

The costs for leveling are primarily estimated by the distance surveyed. Within reason, the number of points surveyed is not a factor. Surveying 20 points along a 1-mile path costs very little more than surveying only 1 or 2 points along that path. In fact, Johnson - Frank, Inc., leveled 49 bench marks rather than the 20 set forth in the contract; leveling through all available benchmarks costs no more than leveling around them. .

Highlights:

For the Southern California project, GPS costs were 39% those of leveling, and accuracy was comparable.

For the Northern California project, GPS costs were 74% those of leveling, and accuracies were debatable.

For the North Carolina project, cost data were not available, but GPS times were only 27% those of leveling, and accuracy was comparable.

In general, leveling costs are distance based, whereas GPS costs are point based. GPS is clearly the key in linking the NHS network nationwide.

Costs for leveling can and will increase significantly in hilly or mountainous terrain. The average leveling costs were $684.38 per kilometer in flat terrain, and $1,352.22 per kilometer in hilly terrain. Here, GPS again has the advantage. It makes little difference in GPS surveying whether the baseline is level or extends into the mountains, other than the travel time required between the two ends of the baseline.

Adverse weather impacts both leveling and GPS, but in different ways. Leveling is not performed in the rain, and both leveling crews were delayed two days because of rain. GPS operations can proceed in the rain; but during these demonstration projects, one GPS session was stopped as a weather front was passing through the area. NGS' guidelines require meteorological data (normally, wet- and dry-bulb temperatures, and atmospheric pressure) to be collected regularly and especially immediately before and after an obvious weather front passes during a session, if possible. Atmospheric pressure measurements must be made at approximately the same height as the GPS antenna phase center. Even though these data may not be used in the vector processing, they may be helpful during the analysis of the results and in future reprocessing with more robust software.

From an accuracy perspective, leveling extends orthometric heights more accurately from one point to the next; and GPS extends ellipsoid heights more accurately from one point to the next. For GPS-derived orthometric heights to approach the accuracy derived from leveling, the geoid model needs to be as accurate as possible. Therefore, any effort to improve and evaluate the accuracy of NGS' geoid model, nationwide, serves to directly improve the utility of GPS nationwide.

The northern GPS demonstration project was essentially a worst-case scenario. Differences between the height systems were evident. These differences need to be evaluated. If GPS alone had been used, no one would have been aware that the orthometric heights were poor. It took a combination of GPS, leveling, and NAVD 88 heights to bring out the best in each. This was the major lesson learned from these projects.

Until NGS' geoid model is evaluated nationwide, every GPS surveyor will be uncertain as to the accuracy of GPS-derived orthometric heights. NGS' geoid model cannot be sufficiently evaluated nationwide until the NHS is implemented.

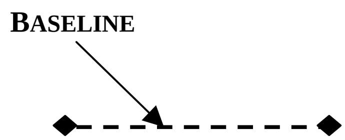
The next four pages address the expansion of surveys from single baselines into complex networks. Although five (5) GPS receivers are used in the following examples (GPS base station plus four "rovers"), efficiencies will be further improved as additional GPS receivers are used for simultaneous observation of multiple baselines.

- **The GPS network will have superior relative and absolute accuracies of 3-D coordinates. Additional GPS receivers form a stronger network of simultaneous baselines, and multiple GPS surveys relative to an assumed base station cause that station to approach the accuracy of a 3-D HARN point.**

- **With network point spacing of 10 Km, the estimated cost savings are 88%, and the estimated time savings are 94%.**

5.5.1 Cost Comparisons – Single Baselines

For two points connected by a single baseline with lengths between 1 and 10 kilometers, the comparative costs between leveling and GPS are shown in Table 16. The results are plotted by the graph at Figure 16.



Single Baseline Length	Leveling Costs	GPS Costs	GPS Savings
1 Km	$680	$1,620	-138%
2 Km	$1,360	$1,620	-19%
3 Km	$2,040	$1,620	21%
4 Km	$2,720	$1,620	40%
5 Km	$3,400	$1,620	52%
10 Km	$6,800	$1,620	76%

Table 16 Comparative Costs for Single Baselines

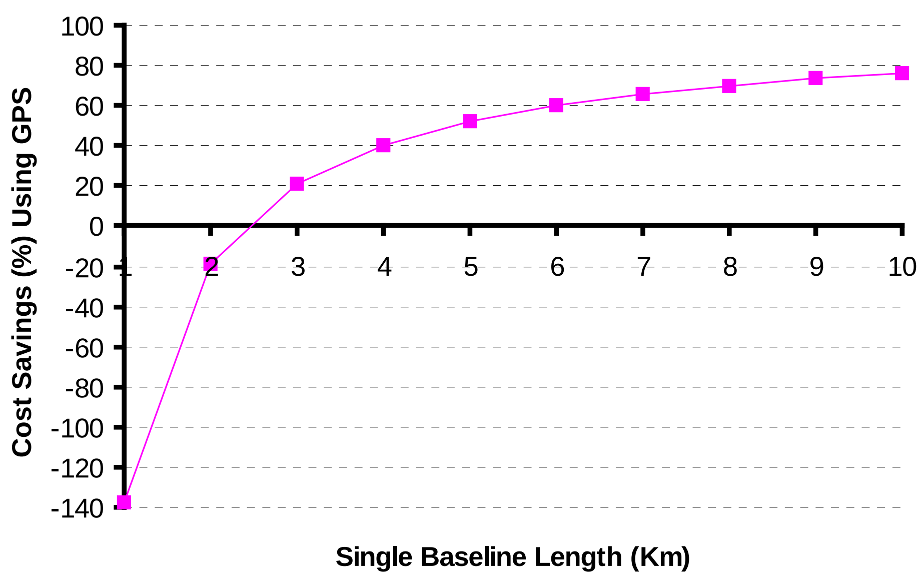
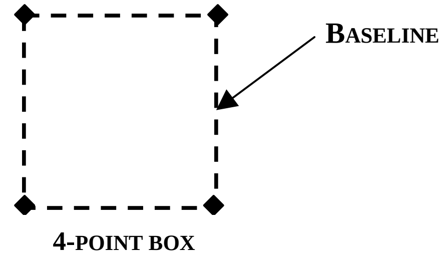


Figure 16 GPS Cost Savings (%) for Single Baselines

Cost Comparison – Multiple (Network) Baselines

For an expanding network with four new points at a time forming multiple baselines, with each baseline length between 1 and 10 kilometers, the comparative costs between leveling and GPS are shown in Table17. The results are plotted by the graph at Figure 17.



Network Baseline Length	Total Leveling Length	Leveling Costs	GPS Costs	GPS Savings
1 Km	4 Km	$2,720	$3,240	-19%
2 Km	8 Km	$5,440	$3,240	40%
3 Km	12 Km	$8,160	$3,240	60%
4 Km	16 Km	$10,880	$3,240	70%
5 Km	20 Km	$13,600	$3,240	76%
10 Km	40 Km	$27,200	$3,240	88%

Table17 Comparative Costs for Multiple (Network) Baselines

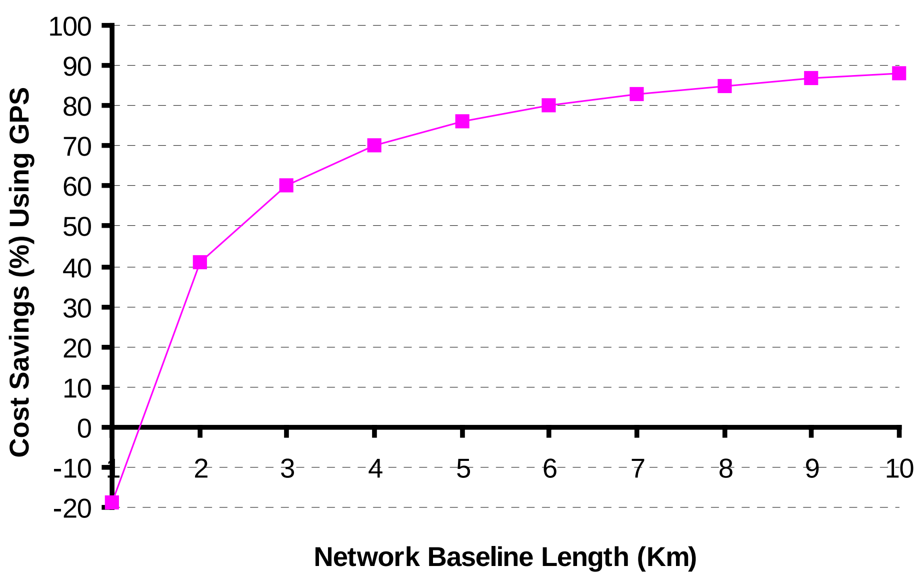
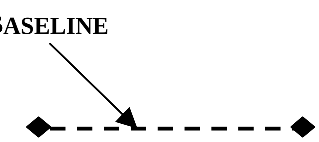


Figure 17 GPS Cost Savings (%) from Multiple (Network) Baselines

5.5.2 Time Comparisons – Single Baselines

For two points connected by a single baseline with lengths between 1 and 10 kilometers, the comparative survey times between leveling and GPS are shown in Table 18. The results are plotted by the graph at Figure 18.



Single Baseline Length	Leveling Staff Hours	GPS Staff Hours	GPS Savings
1 Km	12.8	16.6	-29%
2 Km	25.6	16.6	35%
3 Km	38.4	16.6	57%
4 Km	51.2	16.6	66%
5 Km	64.0	16.6	74%
10 Km	128.0	16.6	87%

Table 18 Comparative Times for Single Baselines

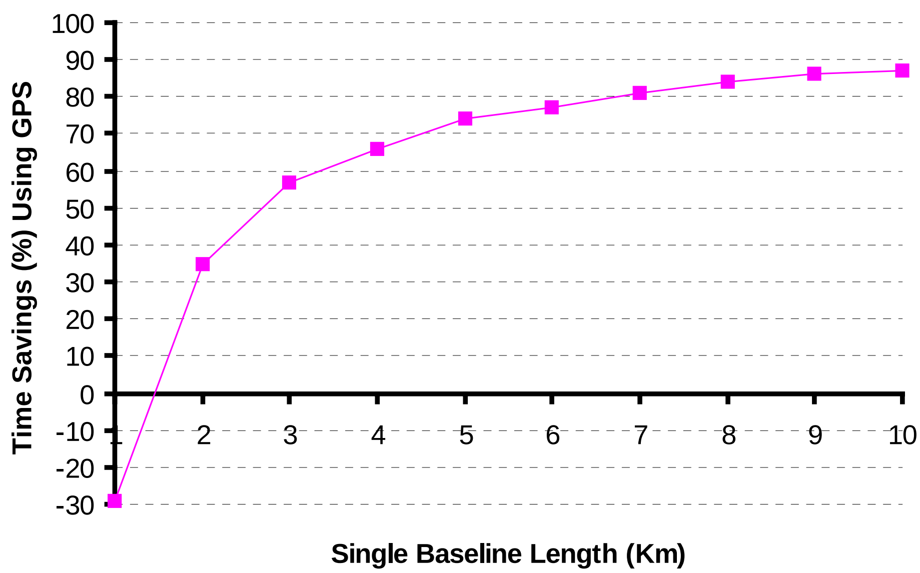
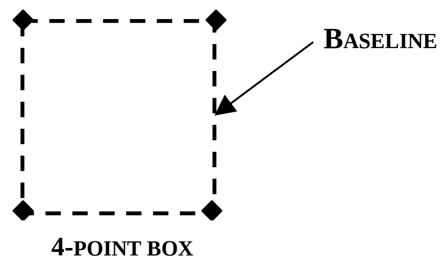


Figure 18 GPS Time Savings (%) for Single Baselines

Time Comparison – Multiple (Network) Baselines

For an expanding network with four new points at a time forming multiple baselines, with each baseline length between 1 and 10 kilometers, the comparative times between leveling and GPS are shown in Table19. The results are plotted by the graph at Figure 19.



Network Baseline Length	**Total Leveling Length**	**Leveling Staff Hours**	**GPS Staff Hours**	**GPS Savings**
1 Km	4 Km	51.2	33.2	35%
2 Km	8 Km	102.4	33.2	68%
3 Km	12 Km	153.6	33.2	78%
4 Km	16 Km	204.8	33.2	84%
5 Km	20 Km	256.0	33.2	87%
10 Km	40 Km	512.0	33.2	94%

Table 19 Comparative Times for Multiple (Network) Baselines

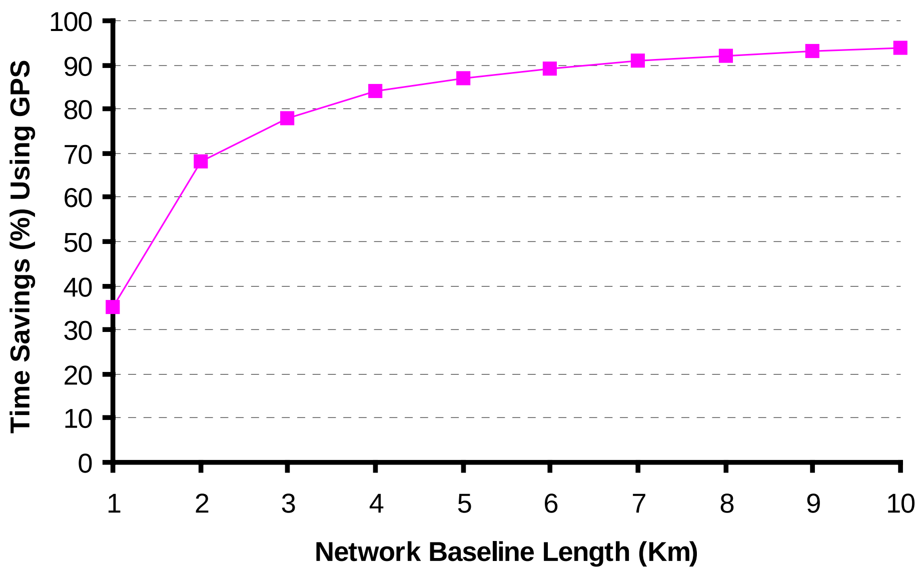


Figure 19 GPS Time Savings (%) for Multiple (Network) Baselines

The leveling times reflect both the impact of leveling over hilly terrain in North Carolina and the flat terrain in both California projects. On the other hand, GPS is terrain independent.

Although GPS averaged 32% more expensive per hour than leveling, it proved far more efficient and quickly becomes more cost effective as displayed in the tables and graphs above. The actual costs of the two California projects averaged $71.42/hour for leveling and computations, and $94.54/hour for GPS surveys and computations. These were costs actually incurred, rather than contracted costs based on a priori estimates and known labor rates.

6 -- FINDINGS

Five major findings were distilled from users needs assessments, presented at the user forums, and follow-up discussions and clarifications from users in principal application categories. Where possible, cost-benefits are provided.

6.1 Finding #1. America needs a "reliable" and efficient means to determine "absolute" elevations, relative only to the earth's center.

- The word "reliable" is in quotes because America (and the world) needs GPS to be secure from jamming, free from Selective Availability that deliberately degrades the GPS signals, and upgraded with additional civil frequencies to improve GPS performance in cities, forests, and other places with obstructed vision of the sky.

- The word "absolute" is in quotes because most elevations in use today have "relative accuracy" rather than "absolute accuracy." Benchmark elevations are: (1) relative to the accuracy of other benchmarks from which leveling was performed, (2) relative to survey procedures used, (3) relative to the distance surveyed inland from "mean sea level," and (4) relative to the route surveyed to get to the current benchmark. It is virtually meaningless to say that a benchmark is accurate to 2-cm (at the 95% or other confidence level), for example, because leveling accuracies refer to X parts per million or similar relative measurement statistics. The same is not true of GPS, when surveys are referenced to CORS stations.

- NGS already operates many CORS stations that are surveyed so well they are assumed to have zero errors relative to the earth's center. This means that all GPS surveys relative to the CORS essentially have "absolute accuracy."

- NGS already publishes guidelines for GPS elevation surveys at the 2-cm and 5-cm levels relative to the CORS.

- NGS already publishes a Geoid model that enables users to convert from elllipsoid heights (from GPS) to orthometric heights (from leveling). When the Geoid model is further refined, to 1-cm accuracy nationwide, users will be able to reliably survey orthometric heights with accuracies on the order of one inch, relative to the earth's center. This is the ultimate goal of many users.

- This requirement is essentially do-able now, provided resources are available to convert and expand the current (2-D) High Accuracy Reference Network (HARN) into a 3-D network.

6.2 *Finding #2. Based on DGPS and CORS, America needs nationwide implementation of a standardized vertical reference datum as the legal basis for elevation data.*

This finding, too, is technically do-able now, but the needed infrastructure is not fully in place to implement NAVD 88 as described herein. .Figure 24 projects an average growth in GPS usage of $1.49 billion annually for ten years.

Users want to know the elevation of a point, and not be confused by the fact that the elevation is X-feet when using NAVD 88, Y-feet when using NGVD 29, Z-feet when using IGLD85, etc.

Users are universally confused by the bewildering array of vertical datums in use today throughout the United States, many of which are not linked to NAVD 88 or NGVD 29..

Implementation of NAVD 88 is a prerequisite for satisfaction of the remaining modern height requirements.

6.3 *Finding #3. America needs high accuracy, high resolution Digital Elevation Models (DEMs) based on NAVD 88.*

- Although they are the most cost-effective DEMs available to the present time, DEMs available from USGS have three major limitations: (1) their elevation accuracy is relatively poor (root mean square errors of 7 meters for Level 1 DEMs; 10 feet for Level 2

DEMs); (2) their point spacing is too wide (typically 10 to 30 meters); and (3) they are produced to the NGVD 29 datum.

- LIDAR and/or IFSAR DEMs solve all three of these problems, but at a price. Although cost estimates vary, it currently costs USGS an estimated $75 per square mile for photogrammetric contouring of quad maps, additional costs for production of hypsography and hydrography DLGs if required, plus $10 per square mile to produce the Level 2 DEMs. When mass-produced, the most accurate DEMs produced from LIDAR would cost an estimated $500 per square mile.

- As a less expensive alternative, IFSAR-generated DEMs (1-3 meter accuracy) could be produced nationwide for an estimated $100 million, i.e., as low as $25 per square mile when mass-produced.

- In five years using IFSAR and/or LIDAR, America could have DEMs with elevation accuracy measured in inches or feet, rather than meters. The DEM point spacing would be 5- to 10 meters, rather than 10 to 30 meters. The vertical datum would be NAVD 88, rather than NGVD 29. The DEMs would be so good that contour lines could be generated at any desired contour interval, bypassing conventional lengthy and costly photogrammetric contouring; and these DEMs would support the production of larger-scale digital orthophotos. With LIDAR and/or IFSAR DEMs, virtually every American would benefit from the data, and the benefit-cost (B/C) ratio would be large, benefiting virtually every user application evaluated in this study.

Areas with DEM Applications	Estimated Value to Constituents	Explanation of Benefits
Nationwide Terrain	**$33.5 million**	• Replace less-accurate Level 1 DEMs that cost USGS approximately $33.5 Million • Provide 6" DEMs costing $500 on average per mi^2, in lieu of 1’ contours costing $5,000 per mi^2 • Enable rapid generation of contours for USGS maps and GISs nationwide • Enable 3-D modeling by USACE, FHA, FRA, FAA, EPA, USFS, etc.
Nationwide Watersheds	**$100 million**	• Automated hydrologic modeling by NWS and FEMA to predict locations/ volumes of peak water concentrations

Special Flood Hazard Areas (SFHAs)	**$225+ million**	• Automated hydraulic modeling by FEMA to determine depth and extent of flood waters • Determination of flood risks and insurance rates
Coastal Erosion Zones	**$11.25+ million**	• Accurate determination of coastal erosion rates • Determination of insurance rates
Urban Areas	**$500 million**	• Urban planning • Intelligent Transportation System (ITS) planning • Elevation layer in GIS database • Stormwater management
Farm Lands	**$1.7 billion**	• Precision farming for planned application of water, fertilizer, etc. • Control of unwanted run-off and stream contamination
Forest Areas	**Not estimated**	• Quantification of timber volumes • Models for spread of wildfires • Plans for wildfire mitigation
HAZMAT Areas	**Not estimated**	• Analyses of contaminated sites • Plans for clean-up
Totals	**$2.5+ billion**	

Table 20. High Accuracy DEM Beneficiaries

6.4 *Finding #4. Based on NAVD 88, America needs a Nationwide Differential GPS (NDGPS) system for real-time accurate 3-D positioning; for navigation, tracking, public safety, precision farming, and construction*

- America needs the NDGPS proposed by the Department of Transportation, and championed by the U.S. Coast Guard (USCG) and the Federal Railroad Administration (FRA). Using surplus Air Force communications equipment, the NDGPS pilot project in Appleton, Washington is working perfectly. Every American who drives a modern vehicle or uses modern telecommunications in the future, and every farmer who uses precision farming, would benefit from this initiative. The B/C ratio is several hundred to one, when justified solely on the basis of horizontal positioning benefits to America. The B/C ratio improves significantly when its 4-dimensional benefits (latitude, longitude, elevation, and time) are taken into account. The 15-year life-cycle costs for NDGPS are only about $70 million, and the benefits to America are in excess of $100 billion.

NDGPS Applications	Estimated Value to Constituents	Explanation of Benefits
Vehicle Positioning and Safety	**$8.385 billion**	• Automated Vehicle Location (AVL) • Computer-Aided Dispatching (CAD) • Intelligent Transportation System (ITS)
Train Location and Safety	**$67.34 million**	• Positive Train Location (PTL) • Positive Train Separation (PTS)
Maritime Navigation and Safety	**$9.6 billion**	• Positioning of dredges • Positioning of cargo ships
Mining and Heavy Construction	**$90 billion**	• Computer-Aided Earthmoving System (CAES), estimated 10% of total savings from GPS modernization • Real-time control of equipment
Precision Farming	**$1.803 billion**	• Real-time control of farm equipment • Controlled application of water, fertilizers, pesticides, etc.
Forest Management	**$6.83 million**	• Real-time positioning
Environmental Protection	**$6.33 million**	• Real-time positioning and damage assessments
Disaster Response	**$7.5 million**	• Real-time positioning and damage assessments • Geocoded addressing when street signs and normal address system fails
Surveying Industry	**Not estimated**	• Vastly improved survey procedures
State/Local Governments	**$178.05 million**	• AVL and CAD for police and other E-911 vehicles • Infrastructure surveys and management
Totals	**$110.052 billion**	**Over the 15-year life-cycle of NDGPS**

Table 21. NDGPS Beneficiaries

6.5 ***Finding #5*. America needs cost-effective, mass-produced GPS elevation surveys of all buildings in or near floodplains, as well as coastal areas vulnerable to hurricane tidal surges, that are based on NAVD 88.**

America needs accurate GPS elevation surveys, mass-produced for an estimated 10,000,000 flood- and hurricane-prone buildings in or near known flood hazards, in order to: (1) implement proactive floodplain management, (2) resolve uncertainties as to flood risk, and (3) get owners of floodprone buildings to purchase needed flood insurance. FEMA knows that horizontal criteria, used by the mortgage industry for flood risk determinations, needs to be replaced with accurate elevation surveys and vertical criteria; NHS implementation proposed here will help solve this. Although this requirement carries a nationwide "price tag" of approximately $1 billion, elevation surveys would pay for themselves in one year if only half the owners of flooded buildings had been convinced to purchase flood insurance. This would reduce dependence on Federal "bail-outs" ($2+ billion per year) when inevitable floods occur.

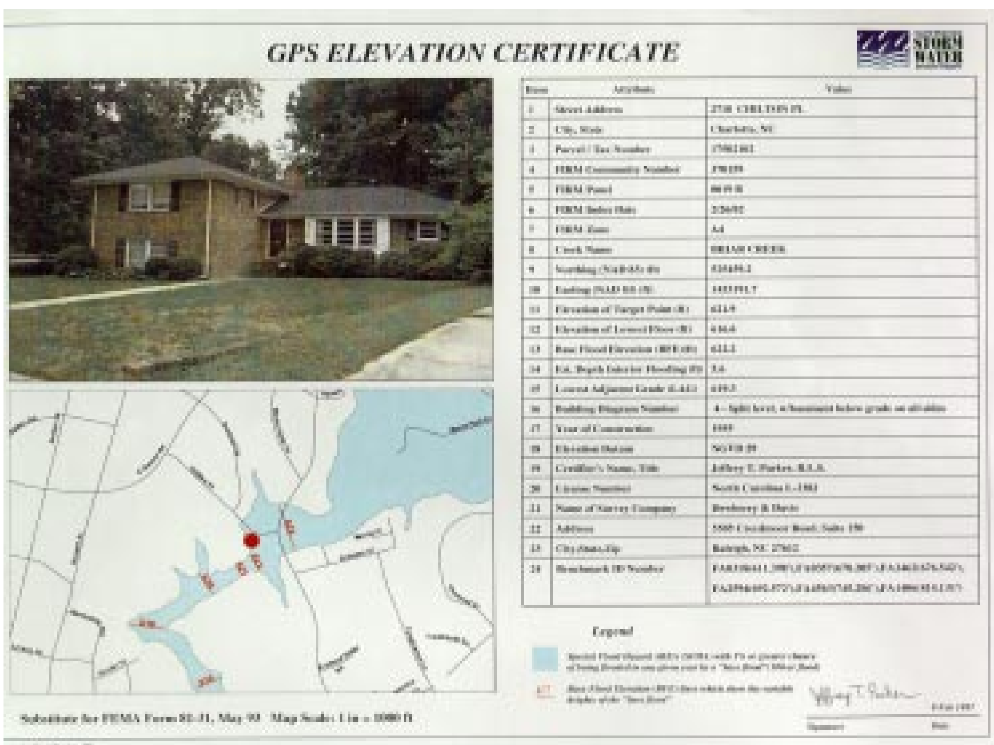


Figure 20 GPS Elevation Certificate (Pre-Flood)

Beneficiaries of this initiative would include the following, all of whom need to know the true flood risk of individual buildings: (1) potential owners, (2) real estate industry, (3) mortgage industry, (4) insurance industry, (5) construction industry, and (6) local government officials.

When hurricanes are accompanied by tidal surges, FEMA needs to quickly survey the breadth and depth of tidal surges, and the elevation of individual damaged buildings, to determine those eligible for home owner insurance reimbursement (wind damages only). Most home owner policies do not cover floods or hurricane tidal surges. Such elevation surveys would be proactive if performed prior to natural disasters, and used to mitigate potential losses.

Strong arguments can be made that Flood Insurance Rate Maps (FIRMs) would not be required if GPS Elevation Certificates were available for all buildings in or near floodplains. Flood Insurance Studies (FIS) would still be required to the point where Base Flood Elevations (BFEs) are computed. Whereas the Special Flood Hazard Area (SFHA) boundaries on FIRMs (the horizontal criteria) indicate broad areas vulnerable to flooding, the GPS Elevation Certificates indicate actual depths of interior flooding, for individual buildings, for the 100-year (1% annual chance) base flood, based on BFEs (the vertical criteria). Thus, specific flood risks would be accurately determined for individual buildings (suitable for flood insurance actuarial rate determinations) based on vertical criteria, as opposed to generalized flood risks for all buildings in SFHAs, based on horizontal criteria. ACCURATE VERTICAL CRITERIA COULD REPLACE CONTROVERSIAL HORIZONTAL CRITERIA IN FLOOD RISK DETERMINATIONS, SOLVING A MAJOR PROBLEM CONFRONTING 15 MILLION NEW HOMEOWNERS ANNUALLY IN THE UNITED STATES.

North Carolina leads the nation in terms of "proactive floodplain management." Floods are our most predictable natural hazard, and GPS Elevation Certificates, such as shown in Figure 20, certify the elevation of the lowest adjacent grade, the lowest floor, and the base flood elevation (BFE), from which the depth of interior flooding is computed for the 1% annual chance flood. This is the most understandable and authoritative document for flood hazard/risk assessment – the first step of "flood mitigation." It is not true that "floods happen, and there's not much we can do about it." There are in fact many proactive steps that can be taken to reduce the risk of potential floods, and reduce the pain and loss when floods occur.

7 -- RECOMMENDATIONS

7.1 Summary

As has been discussed in this report, the North American Vertical Datum of 1988 (NAVD 88) is the practical realization on the ground of a sophisticated elevation reference system for the North American continent. It is designed to be integrated into a seamless network of horizontal and vertical reference points, gravity data, GPS satellites, and tracking stations. This proposed National Spatial Reference System (NSRS), with NAVD 88 as its elevation reference, would support such diversified uses as:

- Precise navigation and aircraft landing systems
- Floodplain management and the National Flood Insurance Program
- Highway and railroad transportation infrastructure
- Intelligent vehicle highway systems
- Earthquake, volcanic, and subsidence research programs
- Disaster preparedness and relief efforts
- Water supply and delivery infrastructure
- Precision agriculture
- International boundaries and offshore boundary mapping
- Coastal zone management
- Environmental cleanup and ground water monitoring

While NAVD 88 was designed and executed over seven years ago, its implementation into the NSRS has yet to be achieved, and its deficiencies in certain regions threaten its very existence. In California, only 30% of the existing vertical control monuments were ever included in NAVD 88 because of their uncertain stability. Of this network of 17,000 NAVD 88 monuments, subsidence or seismic activity has now significantly disturbed 25%. Similar subsidence issues exist in Texas, Louisiana, Florida, South Carolina, North Carolina, Kentucky, Ohio, Virginia, New Jersey, New York, Michigan, and Minnesota. The National Academy of Sciences has estimated subsidence damage costs in each of these states to exceed $10 million annually. Relatively small changes in elevation often have profound impact. For instance:

- The National Research Council conservatively estimated the costs resulting from increased flooding and structural damage from subsidence in the United States to be in excess of $125 million per year.

- The California Department of Water Resources estimates aquifers in the state are over drafted by 10 million acre-feet annually—an increase of 75% over the last five years.

- The National Science Foundation in conjunction with JPL, NASA, Scripps Institute, UCLA, and USGS provided $7.5 million in funding in 1996 for GPS earthquake research.

The use of the 750,000 precisely located, in-the-ground or monumented reference points installed over the past 200 years to measure heights is not adequate to meet the needs of today's mobile and technology-driven society. The classical "line-of-sight" measurements do not provide the real-time accuracy needed for today's positioning technologies and applications, including precision agriculture, efficient marine transportation, and zero visibility landings of aircraft. In addition, many of these reference points have been disturbed, destroyed, or are not in compliance with today's requirements for accuracy.

The implementation of NAVD 88 means densifying the network through recomputation of existing data and execution of new surveys and studies to bring the horizontal, vertical, and gravity control networks together into a unified system joined and maintained by GPS. US Code, Title 33, Section 883 and the Office of Management and Budget Circular A-16 (revised October 19, 1990) specify this authority and responsibility to be the mission of the National Geodetic Survey.

NGS has been unable to apply appropriate resources to undertake a comprehensive solution to the challenge. What is needed is a Nation-wide effort for height modernization led by pilot or demonstration projects in the most difficult and time-critical areas of crustal motion under the direction and expertise of NGS. This is fully compatible with the agency's official charge and its recently published mission, vision and Goals. New surveys and studies would be accomplished under contracts to private firms promoting the goals of economic benefit and technology transfer. Development of standards, contracting oversight, technical supervision, final analysis, and publication would be conducted by NGS ensuring consistency and complying with existing local legislation. In its finished state, the NSRS and NAVD 88 would provide a consistent three-dimensional framework for positioning throughout North America that is fully compatible and maintainable by GPS and/or other space-based navigation systems. The combination of an improved national height system (North American Vertical Datum of 1988–NAVD 88) first adopted by the Federal government in 1993, with the positioning technology of the GPS, offers the nation and its governments, for the first time, the ability to obtain precise vertical measurements in real-time.

7.2 Desired Outcome/Objective

The most desirable outcome is a unified national positioning system, comprised of consistent, accurate, and timely horizontal, vertical, and gravity control networks, joined and maintained by GPS and administered by the National Geodetic Survey (NGS).

A state-of-the-art National Spatial Reference System (NSRS) with NAVD 88 as its elevation reference can make available to the nation a common, consistent set of real-time geographical coordinates or reference points. The applications of this break-through national positioning system will provide:

- Improved coastal and harbor navigation allowing for greater cost-effective transshipment of goods,
- Advanced surface transportation control and monitoring,
- Production of accurate Digital Elevation Models (DEM) allowing for better floodplain analysis and flood insurance needs,
- Highly efficient fertilizer and pesticide spreading, resulting in reduced run-off water pollution and more competitive farming through lower costs and higher crop yields,

- More accurate modeling of storm surge and pollution trajectories,
- Better monitoring of crustal movement to allow for improved understanding of tectonic movement and improved earthquake resistant designs,
- Increased reliability for improved resource management decision making though the use of Geographic Information Systems,
- Support the modernization of our transportation infrastructure and the mission and goals of the Intermodal Surface Transportation and Efficiency Act (ISTEA),
- Improved airline and aircraft safety through GPS controlled approach and landing, and
- Accurate and consistent vertical data for building major cross border projects with Canada and Mexico in support of America's environmental objectives.

7.3 Recommendations for Implementing NAVD 88

7.3.1 Approach

To implement NAVD 88 throughout the United States, an approach is recommended that involves both Federal and private sector forces. Realizing that this implementation will carry a high short-term cost and an ongoing implementation cost, a two-phased approach is recommended. The first phase would focus on the survey work needed to establish the NAVD 88 reference bench marks, while the second phase would expand the system to more users.

Phase 1

Phase one would be a cooperative effort between Federal and private sector forces to establish the **Federal Base System (FBS)** a nationwide network of 3-D control monuments with 10-kilometer spacing, over a recommended period of 5 years. It would include:

(1) Geodetic surveying; activities associated with the projects, including identification of monuments to determine which monuments are suitable for GPS occupation in the project areas; performing leveling and collecting GPS observations; processing and adjusting GPS and leveling data; and preparing reports and submitting results for publication.

(2) Development of a capability within the NGS to manage the implementation effort, determine priority areas, select qualified private sector contractors, manage contracts, and provide technical supervision.

(3) Analyze and document the accuracy of the heights obtained by the projects.

(4) Publish GPS-derived ellipsoid and orthometric heights with their associated accuracy.

(5) Perform technology transfer activities, including publishing non-technical documents describing NAVD 88 and GPS heights,

(6) Conducting seminars to promote understanding of NAVD 88 and GPS for non-technical persons and technical personnel,

(7) Developing training seminars for technical persons to become instructors in the use of GPS to implement NAVD 88, and

(8) Presenting workshops to train the private sector to properly process and submit GPS and leveling data to NGS

It is recommended to use private sector firms to provide the necessary field and GPS survey work to survey the FBS. All private sector work would be out-sourced on a project basis in accordance with Qualification Based Selection (QBS) procedures and the Federal Acquisition Regulations (FAR). All contacting would be carried under the direct supervision of NGS.

Phase 2

Phase two would be the ongoing expansion of the Federal Base System, and it should be carried out under the direction of the NGS. The maintenance effort would be funded on a yearly basis and would involve the cooperation of the states. This is similar in nature to the methods used to maintain the horizontal reference systems in place today. It would involve the expertise of the NGS through their State Advisor program.

State-by-State Implementation

The most cost effective and manageable method to implement the Federal Base System for NAVD 88 throughout the continental United States will be on a state-by-state basis. It will be the responsibility of the NGS to set the priorities for each state, based on the following criteria:

- Amount of seismic activity and subsidence within the state,
- Degree of urbanization and development,
- Needs of the user community, and
- Support for the program within the state.

Once the priorities have been established, the NGS will develop a work plan consisting of a technical scope of work, schedule, and budget for each target state. This work plan will be used to set the level of funding for the term in which the implementation will be carried out.

Demonstration Projects

Two of the states having the greatest immediate need for the full implementation of NAVD 88 are California and North Carolina. Both states are subject to extreme seismic activity, subsidence, floodplain management, coastal erosion, and heavy urbanization. With this report, it is recommended that two demonstration projects be undertaken simultaneously at the inception of phase one. These demonstration projects would accomplish the following mission and be completed during the first year of the program:

- Develop the needed program management capabilities within NGS. This will allow the NGS to put in place the necessary internal procedures and staffing to manage this effort;
- Allow the NGS to develop the proper Federal procedures for out-sourcing of field survey and technical services;
- Train internal NGS staff in the requirements for contract management and technical supervision;
- Test the ability of private sector contractors to carry out this mission;

- Refine technical requirements and standards for using GPS for providing the required degrees of precision;
- Develop a more precise cost model for the implementation of NAVD 88 in the remaining states; and
- Provide a status report, to the House, detailing the program's progress, recommendations for the next phase and level of funding, benefits incurred, and lessons learned.

7.3.2 Time Frame

The sooner the Federal Base System for NAVD 88 is fully implemented, the sooner the Nation will be able to reap the benefits. The program could be implemented over a period of five to ten years depending upon the level of funding available. Using a combination of Federal and private sector forces, this time frame is entirely feasible. However, this cannot happen without additional resources as described below.

7.3.3 Costs

Tables 22 and 23 show the estimated costs for implementing the Federal Base System, including NAVD 88, at a basic 10-kilometer spacing. This includes all costs for providing new field surveys and oversight by the NGS. Table 22 indicates the estimated costs for the first phase demonstration projects, and Table 23 includes costs for nationwide implementation.

7.3.4 Methodology

To best serve the user community, a Federal Base Network is recommended, based on a nominal 10-kilometer spacing of permanent NAVD 88 reference points. This will allow for the maximum effective use by the highest percentage of users. A vast majority of the private survey firms in the United States are small businesses, with staffs under 10 persons. These firms generally cannot afford the cost for advanced GPS technology, the type needed to produce precise and accurate heights. Until the cost for this GPS technology reaches an affordable level, these firms will rely on the use of leveling to serve the height needs of their communities and clients. A denser, 5-kilometer spacing, while recommended in the urban areas, would cost almost four times as much as the 10-kilometer spacing.

Nominal spacing of 10- kilometers would yield approximately 55,000 permanent NAVD 88 reference points throughout the continental United States, (eliminating points where monuments are obviously not required) at an average cost of approximately $1,200 per 3-D survey monument. The $1,200 estimate is based on the approximate $800 average cost of observing with GPS plus an estimated $400 required to cover the point's reconnaissance, monumentation, and administrative costs. This would allow the local surveyor or engineer easy access to the system. In no case would they have to travel more than 5 kilometers (3.1 miles) to gain access to the system. This would allow for more cost-effective surveys and encourage the use of the system. Spacing greater than 10-kilometers will have a detrimental effect to both of these issues, and defeat many of the benefits described in this report.

Table 22 Phase 1 – First Year Demonstration Projects

Activity	Estimated Cost of Using Conventional Surveying Technologies		Estimated Cost of Using GPS Technologies	
State	**California**	**North Carolina**	**California**	**North Carolina**
Subtotal	**$41,200,000**	**$20,040,000**	**$4,600,000**	**$2,380,000**
TOTAL	**$61,240,000**		**$6,980,000**	

Table 23 Nationwide Implementation of the Federal Base System

Activity	Estimated Costs of Using Conventional Surveying Technologies	Estimated Costs of Using GPS Technologies
TOTAL	**$596,000,000**	**$66,000,000**

8 -- APPENDIX

This Appendix provides detailed technical background to clarify discussion in the remaining chapters of the report

8.1 National Spatial Data Infrastructure (NSDI)

Information about where an object or feature is or where an event takes place often is an important factor in decision making in both the public and private sectors. Geospatial data, which identify the geographic location and characteristics of natural or constructed features and boundaries referenced to the earth, provide a unique context for integrating otherwise disparate observations and for evaluating competing options. Factors of location, distance, pathways, and other spatial relations often must be considered when making decisions about economic ventures, resources management, environmental and health concerns, and responses to emergencies.

Public and private sector organizations have recognized the usefulness of spatial data in their activities. The U.S. spends billions of dollars annually on the collection, management, and dissemination of spatial data. Advances in computer techniques to collect and process spatial data, together with decreasing costs for acquiring these technologies, help organizations using spatial data to do so more efficiently and effectively. Such advances enable other organizations to use spatial data for the first time. Technologies such as the Internet and the World Wide Web enable organizations to make their information more widely available and to locate data produced by others.

The NSDI facilitates data sharing by organizing and providing a structure of relationships between producers and users of spatial data. By participating in the NSDI, Federal, state, regional, and local government agencies; companies; and nonprofit organizations can cooperate to develop consistent, reliable means to share spatial data. Executive Order 12906, "Coordinating Geographic Data Acquisition and Access; the National Spatial Data Infrastructure," dated April 11, 1994, formalized Federal participation in initial efforts to implement the NSDI.

Instructions in this executive order are that Federal agencies will work with non-Federal organizations to develop the NSDI, will document their spatial data and make this documentation available to the public, and will make plans to provide public access to their spatial data. This executive order also instructs agencies to lead in the development of standards.

Office of Management and Budget (OMB) Circular A-16 established the Federal Geographic Data Committee (FGDC) to develop the NSDI. This circular assigns to Federal agencies the responsibilities of leading coordination activities for categories of data, for example:

- The Secretary of the Interior heads the FGDC, and the Department of Interior's U.S. Geological Survey (USGS) is responsible for base cartographic data and geologic data.
- The Secretary of Commerce heads the Federal Geodetic Control Subcommittee (FGCS) of the FGDC, and the Department of Commerce's National Geodetic Survey (NGS) is responsible for Geodetic Control and Bathymetry, major components of the National Spatial Reference System (NSRS).

USGS has responsibilities for standards related to base cartographic and geologic information. NGS has responsibilities for standards related to geodetic control and bathymetry. Other Federal agencies (U.S. Forest Service, National Park Service, Bureau of Land Management, FEMA, Natural Resources Conservation Service, etc.) have similar responsibilities for cadastral, transportation, soils, vegetation, wetlands, floodplain mapping, etc.

The intent is to avoid duplication of effort and provide accurate and up-to-date spatial data most cost-effectively to all.

By participating and encouraging others to participate in the NSDI, the various Federal agencies can realize several opportunities for carrying out their missions. Making their data available through the NSDI increases the opportunities for these data to be used in decisions made at the local, regional, national, and global scales, and it helps to increase the relevance of Federal activities. Through the NSDI, responsible Federal agencies can locate data produced by others that can supplement their data collection efforts, and they can identify organizations that are candidates for collaborative data collection and use.

A major component of the NSDI is the development and implementation of a national digital geospatial data framework. Although applications of digital geospatial data vary greatly, users have recurring needs for a few common themes of data. These data themes (the framework) include orthoimagery, **elevation**, transportation, hydrography, political and administrative boundaries, cadastral, and **geodetic control**.

The recurring needs for these data themes are not being met consistently because of limited investment, gaps in coordination, and a lack of common approaches. As a result, important information is not available for many areas, and multiple organizations support duplicate data activities for other areas. Because no coordinated mechanism exists to maintain and manage the common data being collected by the public and private sectors, costs are higher, and efficiency is reduced for individual organizations, as well as for the Nation.

The purpose of the framework concept is to organize and enhance, throughout all levels of the government and the private sector, the collection, maintenance, and dissemination of basic, consistent digital geospatial data. The framework will facilitate data sharing and provide a base on which an organization can accurately register and compile other themes of data or add application-specific information. Shared collection and maintenance will reduce expenditures for data collection and integration, allow organizations to focus on their primary business, expand the user base for data being collected, and increase data availability over broader geographic areas.

8.2 National Spatial Reference System (NSRS)

NGS' document, *National Geodetic Survey: Its Mission, Vision, and Strategic Goals*, was prepared to describe to the public its implementation of the NSRS, mapping and charting activities, research, public outreach, and other related activities.

As currently envisioned, the NSRS framework, when completed in all 50 states, would include some 16,000 geodetic control stations. Because this number of stations is impractical for NGS to establish and maintain with present funding and human resources, NGS has separated these stations into categories for the purpose of assigning responsibility for establishment and maintenance.

- **The Federal Base Network (FBN)** consists of a very high-accuracy, four-dimensional (latitude, longitude, orthometric height, and time) network of over 1,400 monumented stations with 100-km nominal spacing throughout the U.S. and its territories. The FBN will also contain additional stations as needed in areas of subsidence or crustal motion, or as needed in support of Federal aircraft navigational requirements.

- **The Cooperative Base Network (CBN)** consists of approximately 14,600 three-dimensional (3-D) monumented stations, with 25- to 30-km nominal spacing, established and maintained through cooperative agreements with other Federal, state, and local government agencies.

In order to cost-effectively achieve 2-cm elevation accuracy, DGPS base stations need to be within 10 km of the rover units. For this reason, FBN/CBN point spacing of 25-30 km is inadequate. A nominal spacing of 10 km is recommended.

- **The User Densification Network (UDN)** consists of additional monumented stations, connected to the FBN or CBN in accordance with FGCS Standards and Specifications, which contribute to the public good. These are normally surveyed by the private sector without a cooperative agreement.

To facilitate the User Densification Network, user-friendly "blue booking" programs are required for import of processed GPS files and monument descriptions.

The data management, archiving, and dissemination for both FBN and CBN is the responsibility of NGS. The NGS responsibility for the UDN is to act as the depository and purveyor of control survey data, provided the surveys were performed by or for National, state, or local governments and satisfy rigorous accuracy requirements.

8.3 Vertical Datums

> **After a decade, the North American Vertical Datum of 1988 (NAVD 88) has still not been implemented in major portions of the U.S. In fact, dozens of diverse vertical datums are in use throughout the U.S., with unknown linkage to NAVD 88.**

All measurements made by surveyors to determine and depict horizontal positions and elevations should relate to a "reference datum." The North American Datum of 1983 (NAD 83) has replaced the North American Datum of 1927 (NAD 27) as America's standard horizontal datum. Similarly, the North American Vertical Datum of 1988 (NAVD 88) has replaced the National Geodetic Vertical Datum of 1929 (NGVD 29) as America's standard vertical datum. However, full implementation may never occur, and current deficiencies will worsen, without sustained Federal funding for implementation.

8.3.1 Local Mean Sea Level

America's initial use of local mean sea level as a vertical datum reference was based on the readily observed tidal cycles of mean hourly water elevations observed over a 19-year Tidal Datum.

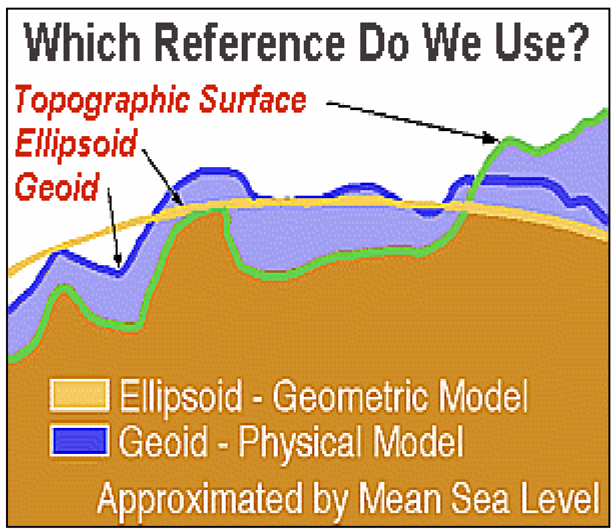


Figure 21 Vertical Datum Reference Options

The arithmetic mean of these observations provided the level used as local mean sea level. However, there are many variables that affect the determination of local mean sea level, and an attempt was made in the 1920s to define a consistent nationwide vertical datum to replace the confusing morass of local datums at every seaport.

8.3.2 National Geodetic Vertical Datum of 1929 (NGVD 29)

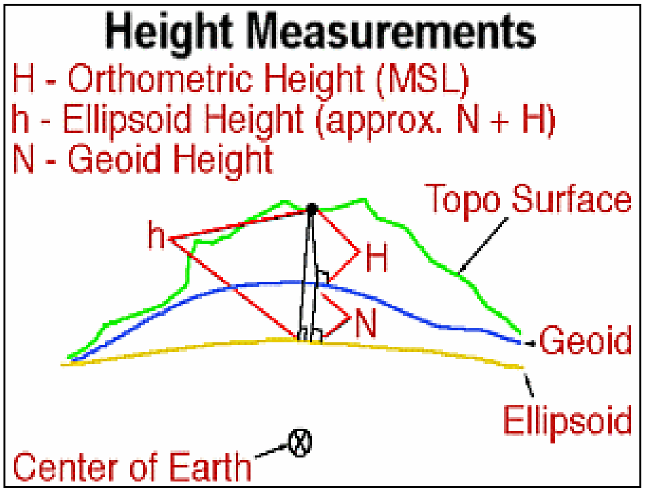


Figure 22 Height Measurements

The National Geodetic Vertical Datum of 1929 (NGVD 29) combined a series of precise leveling surveys, referenced to 21 tide gages in the U.S. and five in Canada. The object of NGVD 29 was to provide a fixed datum that was supposed to bring a consistent relationship to all vertical determinations in the U.S. Until recently, NGVD 29 has been the vertical datum for all maps of the U.S. produced by the U.S. Geological Survey (USGS) and other Federal agencies. As newer data were incorporated into NGVD 29, surveyors and mappers became dissatisfied with the inconsistencies in NGVD 29. Since the advent of GPS, the requirements for change have become obvious, and the technical means are available, affordable, and relatively risk-free.

8.3.3 North American Vertical Datum of 1988 (NAVD 88)

The North American Vertical Datum of 1988 (NAVD 88) was necessary to remove the inconsistencies and distortions in the NGVD 29. For example, first-order elevations leveled from zero NGVD in New York were significantly different from first-order elevations leveled from zero NGVD in Philadelphia. A decision was made by NGS, and its counterpart agencies in Canada and Mexico, to adopt a vertical datum based on a mathematical surface that closely approximates the geoid. Approval and funding to establish the new datum was received in 1978. International in scope and definition, NAVD 88 was constructed from 1.3 million kilometers (800,000 miles) of precise leveling measurements throughout Mexico, the United States, and Canada, and the readjustments of about 600,000 permanent benchmarks. In 1998 dollars, this represents an investment of well over one billion dollars.

Although a Federal Register Notice of June 24, 1993, designated NAVD 88 as the official replacement of the older NGVD 29 datum, it is still acceptable to use NGVD 29 and diverse vertical datums (e.g., Mean Low Low Water (MLLW) Tidal Datums, the 1974 Low Water Reference Plane (LWRP) for the Lower Mississippi River, the International Great Lakes Datum of 1985 (IGLD85), local construction project datums, or other reference planes established by local jurisdictions), provided the relationship of such datums to NAVD 88 is clearly noted and understood. Unfortunately, the distinctions are quite complex and are often misunderstood, and many jurisdictions totally disregard this requirement.

The problems discussed here did not have practical solutions until 1997 when modern aerial survey firms proved that they could cost-effectively acquire high-resolution and high-accuracy Digital Elevation Models (DEMs) nationwide using airborne GPS related to NAVD 88, inertial measuring units (IMUs), and laser and radar sensors to accurately survey the terrain. With such DEMs, GIS specialists would know both the NGVD 29 and NAVD 88 orthometric heights of billions of data points nationwide, and could use computers to compile accurate contour lines at any desired contour interval and to any existing or future vertical datum.

A major problem resulting from conversion from NGVD 29 to NAVD 88 is that nearly all contour lines on USGS and other maps are obsolete. These contour lines were photogrammetrically compiled to NGVD 29, and, with traditional photomapping technology, it is very expensive to recompile these contours to NAVD 88. The least expensive solution is to place a correction note on each map, saying for example that "all NAVD 88 elevations are 2.3 feet lower than the NGVD 29 elevations shown on this map." In other words, the user would need to convert the 10-foot contour line to 7.7 feet, the 20-foot contour line to 17.7 feet, etc. The adjoining map, however, may have a correction of 2.2 feet instead of 2.3 feet. Therefore, at the edge of adjoining maps, where NGVD 29 10-foot contour lines previously joined, one map would convert this contour line elevation to 7.7 feet, and the adjoining map would convert this elevation to 7.8 feet. This presents major problems for users, especially FEMA.

8.4 Relative vs. Absolute Accuracy

The accuracy of orthometric heights has traditionally depended on:

1. **Starting Point:** The accuracy of benchmarks (or 3-D survey monuments) used to extend orthometric heights inland from the oceans

2. **Procedures:** The survey equipment and procedures used

3. **Route:** The *route* taken to survey from the benchmark to the new point(s) for which orthometric heights are required.

All three of these traditional dependencies contribute to elevation problems worldwide.

- Surveyors have long known that NGVD 29 elevations, for benchmarks and 3-D survey monuments, were not sacrosanct. Surveyors found errors and inconsistencies on a daily basis, but little could be done. Since points are surveyed relative to benchmarks that have elevation errors (often of unknown magnitude), all orthometric heights are determined with *relative accuracy*, and not *absolute accuracy*.

- Surveyors have long used "orders" and "classes" to categorize the accuracy of their surveys. First-order, Class I surveys were universally known as the best, and surveyors strove to achieve perfect vertical control surveys with zero misclosures. Here, too, the accuracy of orthometric heights are *relative accuracy*, because each survey "order" and "class" allows specified errors relative to the distance surveyed.

- Geodesists, but few others, recognized that orthometric heights varied according to the <u>*route*</u> used to survey from a known benchmark to an unknown point. This is because local variations in gravity (caused by mass excesses or deficiencies in the Earth's crust) cause the surveyor's plumb bob to point slightly away from the center of the Earth in variable directions. Orthometric heights, relative to diverse traverse or leveling routes, are bewildering to the survey profession. Until GPS and modern gravimeters enabled geodesists to model the geoid, there was no effective way to account for local variations in gravity.

Figure 23 provides an example. For illustration purposes, suppose points A, B, C, and D are on the north, south, east, and west sides respectively of a large, still lake; and suppose points A and B are both at the water's edge. Point C is east of the lake, on a mountainside. Point D is west of the lake, in a valley. One surveyor surveys from A to C to B, and then back to C and A, with zero misclosure; the elevation of point B is determined to be higher than A. Another surveyor surveys from A to D to B, and then back to D and A, also with zero misclosure; but the elevation of point B is determined to be lower than A. Is B higher than A, or lower? Both answers cannot be right -- or can they?

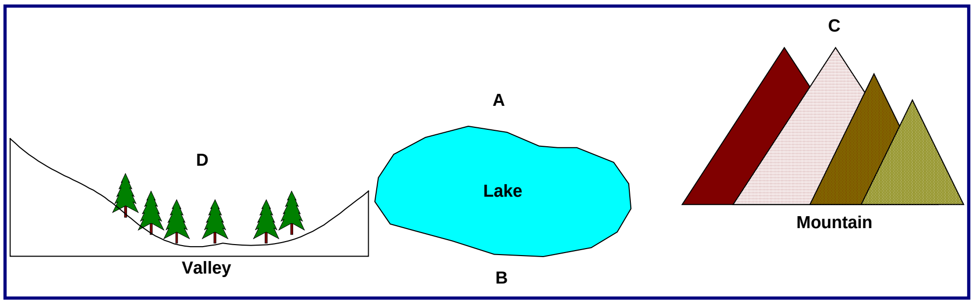


Figure 23 Example of Route-Dependent Elevations

In fact, it is likely that the two elevations at B will differ because of a mass excess (mountain) near point C, and a mass deficiency (valley) near point D. The two surveyors did nothing wrong, yet they ended up with two different orthometric heights for point B, both relative to point A; and both their surveys had zero misclosures. Because water surfaces are equipotential surfaces (having equal forces of gravity), the elevations (technically, the "dynamic heights") of points A and B, by definition, must be equal, but this can be verified only if the surveyor surveys directly over the level (equipotential) surface of the lake between A and B, rather than surveying around the east or west sides of the lake where the directions of gravity are different.

- Precise elevation surveys are routinely performed to monitor land subsidence, intended to ensure the supply of water for human consumption, ranching, and agriculture. In central California, high accuracy leveling erroneously concluded that prior subsidence had stabilized and that some ground was actually rising in elevation. However, GPS surveys from distant Continuously Operating Reference Stations (CORS) proved that the benchmark used for the leveling was subsiding also, at a faster rate than some other points leveled relative to this benchmark. This made some points appear to be rising, relative to the benchmark, when they were in fact continuing to subside.

- Since the advent of the Global Positioning System (GPS) and differential GPS (DGPS), surveyors now determine 3-D coordinates with **<u>absolute accuracy of several centimeters</u>** (2.54 cm = 1 inch) in most locations. Although DGPS is technically a relative survey process, the difference is that GPS surveys can be relative to NGS' CORS that are surveyed so well that their absolute errors are considered to be zero, relative to the Earth's center. **<u>Thus, GPS surveys conducted relative to CORS yield absolute accuracy.</u>**

8.5 NAVD 88 Implementation

While NAVD 88 was designed and made official over seven years ago, its implementation into the NSRS has yet to be achieved, and its deficiencies in certain regions threaten its very existence. In California, only 30% of the existing vertical control monuments were ever included in NAVD 88, because of their uncertain stability. Of this network of 17,000 NAVD 88 monuments, subsidence or seismic activity has now significantly disturbed 25%. Similar subsidence issues exist in Texas, Louisiana, Florida, South Carolina, North Carolina, Virginia, New Jersey, New York, Michigan, and Minnesota. The National Academy of Sciences has estimated subsidence damage costs in each of these states to exceed $10 million annually.

Relatively small changes in elevation often have profound impact. For example:

- The National Research Council conservatively estimated the annual costs due to increased flooding and structural damage from subsidence in the U.S. to be in excess of $125 million.

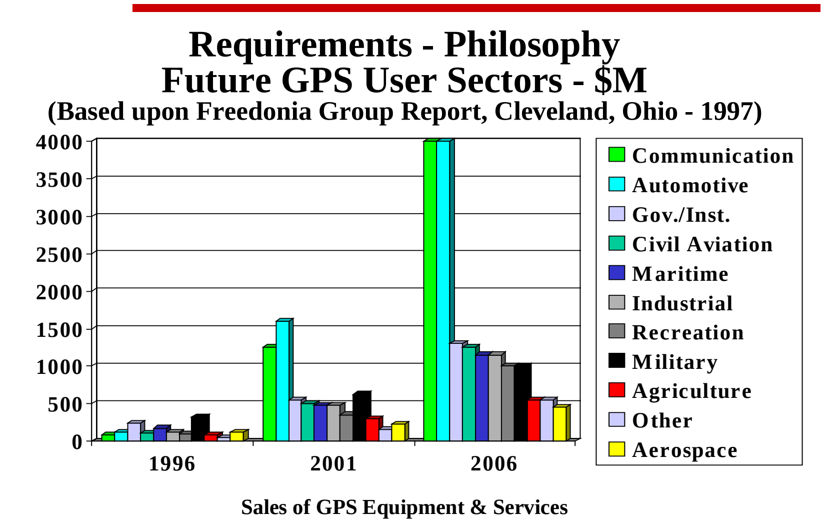
The California Department of Water Resources estimates aquifers in the State are over drafted by 10 million acre-feet annually, an increase of 75% over the last five years.

8.6 Global Positioning System (GPS)

America's Global Positioning System (GPS) *already is* the world's next Utility System. As shown by the chart below, the Freedonia Group and similar organizations project a meteoric rise in GPS users over the next decade, with communications, automotive, and other applications impacting virtually every American. <u>During the past few</u>

years, the National Geodetic Survey (NGS) and others have proven that GPS can provide good 3-D positioning, with accurate heights/elevations, and not just 2-D positioning. Airborne GPS, combined with inertial, laser, and radar sensors, also enable America to satisfy its decades-long requirements for accurate Digital Elevation Models (DEMs) vital to thousands of Federal, state, county, local communities, and private organizations that rely on modern Geographic Information System (GIS) technology for competitive business practices.

Figure 24 Projected Growth in GPS Users



Trying to figure out where he is and where he is going is probably one of man's oldest problems. Navigation and positioning are crucial to so many activities, and yet the process has always been quite cumbersome. Over the years, all kinds of technologies have been tried to simplify the task, but each has had some disadvantage.

- Landmarks work only in local areas. They are subject to movement or destruction by environmental factors.
- Dead reckoning is very complicated. Accuracy depends on measurement tools that are usually relatively crude. Errors accumulate quickly.
- Celestial navigation is very complicated. It works only at night, in good weather.

- OMEGA has limited precision. It is based on relatively few radio direction beacons. Accuracy is limited and subject to radio interference.
- LORAN has limited coverage (mostly coastal). Accuracy is variable and is affected by geographic situation. LORAN is easy to jam or disturb.
- SatNav is based on low-frequency Doppler measurements, so it is sensitive to small movements at the receiver. There are few satellites, so updates are infrequent.

Ultimately, the U.S. Department of Defense developed a technical solution to satisfy operational requirements worldwide. The result is the Global Positioning System (GPS), a system that has changed navigation and positioning forever. Its military value was proven in 1991 during the Mid-East War when GPS-guided cruise missiles and “smart bombs” contributed greatly to the nation’s success. Today, civil GPS users far outnumber military users, and GPS is equally successful for a myriad of innovative applications.

GPS is a worldwide radio-navigation system formed from a constellation of 24 satellites and their ground stations. GPS uses these "man-made stars" as reference points to calculate positions accurate to a matter of meters. In fact, with advanced forms of GPS, it is possible to make measurements to better than a centimeter! In a sense, it is like giving every square foot on the planet a unique address.

GPS receivers have been miniaturized to just a few integrated circuits and so are becoming very economical, which makes the technology accessible to virtually everyone. These days, GPS is finding its way into cars, boats, planes, construction equipment, movie making gear, farm machinery, even laptop computers. Soon, GPS will become almost as basic as the telephone. Indeed, GPS is quickly becoming a universal utility.

- Name: NAVSTAR Manufacturer: Rockwell International
- Altitude: 20,000 Kilometers
- Weight:1900 lbs. (in orbit)
- Size:17 ft with solar panels extended
- Orbital Period: 12 hours

- Orbital Plane: 55 degrees to equatorial plane
- Planned Life Span: 7.5 years
- Current constellation: 24 Block II production satellites
- Future satellites: 21 Block IIR's developed by Martin Marietta.

Ground Stations (also known as the "Control Segment") monitor the GPS satellites, checking both their operational health and their exact position in space. The master ground station transmits corrections for the satellite's ephemeris constants and clock offsets back to the satellites themselves. The satellites can then incorporate these updates in the signals they send to GPS receivers.

There are five monitor stations: Hawaii, Ascension Island, Diego Garcia, Kwajalein, and Colorado Springs.

How GPS works in five steps:

1. **The basis of GPS is "triangulation" from satellites.**
2. **To "triangulate," a GPS receiver measures distance using the travel time of radio signals.**
3. **To measure travel time, GPS needs very accurate timing that it achieves with atomic clocks.**
4. **Along with distance, you need to know exactly where the satellites are in space. High orbits and careful monitoring are the secret.**
5. **Finally you must correct for any delays the signal experiences as it travels through the atmosphere.**

Improbable as it may seem, the whole idea behind GPS is to use satellites in space as reference points for locations here on earth. By very accurately measuring our distance from four satellites, we can "triangulate" our position anywhere on earth.

The GPS provides two levels of service -- a Standard Positioning Service (SPS) for general public use and an encoded Precise Positioning Service (PPS) primarily intended for use by DOD. The SPS provides civil users a worldwide service without charge or restrictions. The SPS accuracy is intentionally degraded by the DOD through the use of a time-varying bias called *Selective Availability* (S/A). SPS (with S/A on) has a predictable accuracy of 100 meters (horizontal) and 156 meters (vertical). If S/A is turned off by DOD, the predictable positioning accuracy of a single GPS receiver will improve to 22 meters (horizontal) and 28 meters (vertical) -- still inadequate for many civil requirements.

8.7 Differential GPS (DGPS)

Basic GPS is the most accurate radio-based navigation system ever developed, and for many applications it is plenty accurate. Differential GPS or "DGPS" can yield meter-level accuracy in moving applications and centimeter-level accuracy in stationary situations. That improved accuracy has a profound effect on the importance of GPS as a resource. With it, GPS becomes more than just a system for navigating boats and planes around the world. It becomes a universal measurement system, capable of positioning things on a very precise scale.

Differential GPS (DGPS) involves the cooperation of two receivers, one that is stationary (at a known point) and another that is roving around making position measurements (at unknown points). The stationary receiver is the key. It ties all the satellite measurements into a solid local reference. GPS receivers use timing signals from at least four satellites to establish a position. Each of those timing signals is going to have some error or delay depending on what sort of perils have befallen it on its trip down to earth. Since each of the timing signals that go into a position calculation has some error, that calculation is going to be a compounding of those errors. The satellites are so far out in space that the little distances traveled here on earth are insignificant. If two receivers are fairly close to each other, within a few hundred kilometers, the signals that reach both of them will have traveled through virtually the same slice of atmosphere, and so will have virtually the same errors. Thus, errors detected at the DGPS base station (known point) are used to correct the positions of the unknown points, simultaneously observing the same four (or more) GPS satellites.

Soon DGPS may be able to resolve positions that are no farther apart than the width of one’s little finger. Automatic construction equipment will be able to translate CAD drawings into finished roads without any manual measurements. Self-guided cars will take “drivers” across town while they quietly read in the back seat. To understand how this kind of GPS is being developed, it is necessary to understand a little about GPS signals, and a little about how surveyors are using GPS right now. Surveyors have been using GPS to do extremely precise surveys for years, fixing points with relative accuracy on the order of millimeters. Furthermore, GPS technology continues to evolve. GPS satellites of the future, with multiple "carrier phase" frequencies are expected to be orders of magnitude more accurate than "code-phase GPS" used today.

8.7.1 DGPS for Air Navigation and Safety

Realizing the capabilities and value of GPS, the Federal Aviation Administration (FAA) is currently implementing a Wide Area Augmentation System (WAAS) based on GPS and geostationary communications satellites. This system will bring the accuracy and reliability of differential GPS across the entire continent and make a great contribution to aviation safety and air traffic control. The idea grew out of some very specific requirements that basic GPS could not handle by itself. It began with "system integrity." GPS is very reliable, but every once in a while a GPS satellite malfunctions and gives inaccurate data. The GPS monitoring stations detect this sort of thing and transmit a system status message that tells receivers to disregard the broken satellite until further notice. Unfortunately, this process can take many minutes, which could be too late for an airplane in the middle of a landing. To counter this anomaly, the FAA will establish its own monitoring system that will respond much quicker. In fact, they figured they could park a geosynchronous satellite somewhere over the earth that would instantly alert aircraft when there was a problem. Then they reasoned that they could transmit this information on a GPS channel so aircraft could receive it on their GPS receivers and without any additional radios. Adding another satellite helps with positioning accuracy, and it ensures that plenty of satellites are always visible around the country!

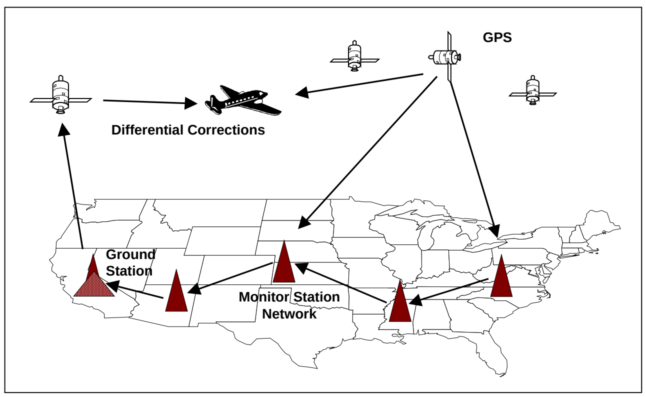


Figure 25 Operation of the FAA Wide Area Augmentation System (WAAS)

The FAA figures that with about 24 reference receivers scattered across the United States, they can gather good correction data for most of the country. This data will make GPS accurate enough for "Category 1" landings (i. e., very close to the runway but not zero visibility). This system is currently being implemented.

To complete the system, the FAA will establish "Local Area Augmentation Systems" (LAAS) near runways. These will work like the WAAS, but on a smaller scale, and perhaps with pseudolites instead of geosynchronous satellites. The reference receivers will be near the runways, and so will be able to give much more accurate correction data to the incoming planes. With a LAAS, aircraft will be able to use GPS to make Category 3 landings (zero visibility). For this to work, height data are critical to within a few centimeters. America's height reference system, NAVD 88, is crucial to the success of LAAS and the ultimate safety of millions of air travelers in the future.

However, other users of DGPS augmentation systems cannot rely on these FAA systems to satisfy ground positioning requirements for the following reasons:

- "This signal reception from the WAAS geostationary satellite represents a serious concern for users on the surface where there is a potential for multipath, shadowing, and blockage of WAAS signals due to natural and manmade obstructions.[26]" Essentially, a geosynchronous satellite designed for optimum communications with in-flight aircraft would not satisfy ground users who regularly have poor visibility to a geosynchronous satellite "parked" over the equator.
- Similarly, LAAS communications would be designed to optimize aviation safety, using aviation frequencies. LAAS DGPS corrections would certainly not focus on the need to penetrate buildings and mountains, as are NDGPS signals. Furthermore, it may not be in anyone's best interest to make compromises that could jeopardize safety for either air or ground travelers.

8.7.2 DGPS for Land Navigation and Vehicle Tracking

Navigation is the process of getting something from one location to another; tracking is the process of monitoring it as it moves along. Commerce relies on fleets of vehicles to deliver goods and services

[26] Arnold, James A., Federal Highway Administration, March 24, 1998, "Geostationary Satellite Coverage", ***Nationwide DGPS Report***, pp. 95-105.

either across a crowded city or through nationwide corridors. So effective fleet management has direct bottom-line implications, such as telling a customer when a package will arrive, spacing buses for the best scheduled service, directing the nearest ambulance to an accident, or helping tankers avoid hazards.

GPS used in conjunction with communication links and computers can provide the backbone for systems tailored to applications in the areas of agriculture, mass transit, urban delivery, public safety, and vessel and vehicle tracking. Consequently, police, ambulance, and fire departments are adopting systems like Trimble's GPS-based AVL (Automatic Vehicle Location) Manager to pinpoint both the location of the emergency and the location of the nearest response vehicle on a computer map. With this kind of clear visual picture of the situation, dispatchers can react immediately and confidently.

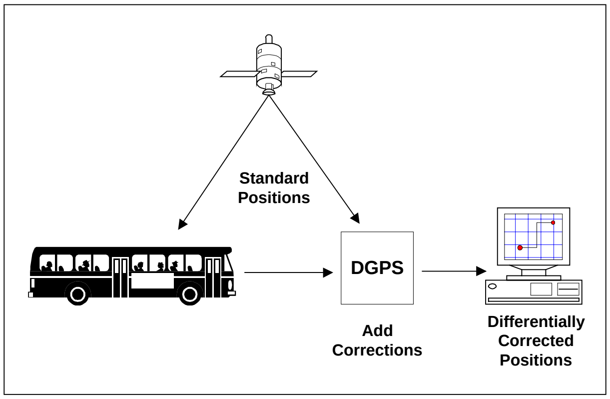


Figure 26 GPS Configuration for Automated Vehicle Tracking

The goal of public safety agencies is to make every emergency response time as fast as possible. When an emergency erupts, an extra second or two can mean the difference between a life saved and a life lost. A dispatcher must make vital decisions in even the best circumstances. The task becomes even more complex in a metropolis like Chicago, with a tangled web of streets and fifteen million emergency calls each year. To help make a difference, Chicago has developed an emergency response system built on GPS based Automatic Vehicle Location (AVL) hardware and software.

Under the old system, Chicago's dispatchers had to make decisions based on data typed on 3"x5" cards. Under the new system, they have all the vital information displayed on the digital maps right in front of them. Dispatchers see the entire city on a digital map allowing 911 calls to be pinpointed instantly. Emergency response vehicles are displayed as icons so the most available unit can be determined. Dispatchers can even zoom in to see building footprints, addresses, even building height, type, and access. This new GPS-based dispatch system displays a wealth of other information, including location of fire hydrants, street directions, and street width. By taking advantage of GPS and by having the tools to immediately identify the best unit to respond, dispatchers will be able to trim seconds (if not minutes) off of response times. A year from now, there will be Chicago citizens alive who simply would not be alive without this new system.

8.8 Nationwide DGPS (NDGPS)

In the early days of GPS, private companies with big projects demanding high accuracy -- groups like surveyors or oil drilling operations -- established their own DGPS reference stations. This is still a very common approach, using a reference receiver and setting up a communication link with your roving receivers. The U.S. Coast Guard (USCG), U.S. Army Corps of Engineers (USACE), and some international agencies are establishing reference stations all over the world, especially around popular harbors and waterways. These stations often transmit on the radio beacons that are already in place for radio direction finding (usually in the 300 kHz range). Anyone in the area can receive these corrections and radically improve the accuracy of their GPS measurements. Most ships already have radios capable of tuning the direction finding beacons, so adding DGPS will be quite easy. Many new GPS receivers are being designed to accept corrections, and some are even equipped with built-in radio receivers.

For maritime safety along U.S. coastlines, the Great Lakes, and the Mississippi River, the USCG and USACE jointly operate DGPS base stations with low frequency/medium frequency (LF/MF) radio beacons that transmit differential GPS corrections in real time to users. At the beginning of 1998, the USCG's DGPS Navigation Service had 54 such DGPS stations in operation (44 in the continental U.S., seven in Alaska, two in Hawaii, and one in Puerto Rico). These DGPS beacon sites, which broadcast differential corrections up to 250 miles away, are extremely effective for multiple users, not just maritime users. In fact, before implementing their system 24 hours per day, the USACE would receive complaints from Midwest farmers within hours of turning off a DGPS station.

Figure 27 Current USCG/USACE DGPS Network

Figure 28 Proposed Nationwide Differential GPS (NDGPS)

With requirements from the Federal Railroad Administration (FRA) for

Positive Train Control, and demands from the farm states for Precision Farming, the U.S. Congress provided $2.4 million in FY98 funds to begin the USCG's expansion into a Nationwide DGPS. The $2.4 million provided funding for reusing and retrofitting six of 66 Ground Wave Emergency Network (GWEN) systems, being decommissioned by the U.S. Air Force, for conversion into DGPS beacon sites. The first such GWEN/NDGPS conversion, in Appleton, Washington, was a total success.

When fully funded, some of the 66 GWEN sites will be converted in place into NDGPS sites, while others will be relocated to other States. Of this total, 54 new NDGPS sites will be in the continental U.S., with 12 more in Alaska—for a total of 120 NDGPS sites. This is one of the largest defense-to-civil conversions in history, and DGPS users throughout America can thank forward-looking innovators in the Federal DOT, U.S. Coast Guard, and Federal Railroad Administration for bringing this capability to the entire country.

When 120 total NDGPS sites are operational, the United States will have redundant DGPS coverage nationwide provided free to all constituents, with availability of 99.999%, continuous integrity monitoring by the USCG to ensure that the system is operating effectively, and nonproprietary standards currently used by dozens of other countries.

8.9 Digital Elevation Models (DEM)

The most persistent requirement expressed by users, from all application, was for high accuracy DEMs, based on a standard vertical datum -- NAVD 88. This section explains the various DEM types available, and their comparative accuracies.

A DEM is the digital cartographic representation of the elevation of the land (z value) at regularly spaced intervals in x and y directions (eastings and northings, or longitude and latitude). This definition of DEM also applies to Digital Terrain Elevation Data (DTED) produced by the National Imagery and Mapping Agency (NIMA). The term "DEM" is sometimes used generically to mean the digital cartographic representation of the earth in any form, rectangular grids or lattices, triangular networks, or irregular spot heights and break lines, for example.

8.9.1 USGS DEM Types

USGS produces several standard types of DEM Data:

- **7.5-minute DEMs** normally have 30- by 30-meter point spacing, using Universal Transverse Mercator (UTM) coordinates on the NAD 27 or NAD 83 horizontal datum and **NGVD 29 vertical datum**. They provide the same coverage as standard USGS 7.5-minute quadrangles (1:24,000-scale map), covering 7.5 minutes of latitude by 7.5 minutes of longitude. Coverage of the entire United States is complete. USGS now offers a 7.5-minute DEM having 10- by 10-meter point spacing. This product is produced when USGS has a cooperator (funding, workshare, Innovative Partnership, etc.)

- **30-minute DEMs** have 2- by 2-arc second point spacing – approximately 60- by 60-meter point spacing in x and y – with geographic coordinates (latitude/longitude) on the NAD 27 or NAD 83 horizontal datums and **NGVD 29 vertical datum**. With half the coverage of a standard USGS 30-minute by 60-minute quadrangle (1:100,000-scale map), it takes two 30-minute DEMs to cover the area of a 1:100,000-scale quad. Coverage of the United States is incomplete.

- **1-degree DEMs** have 3- by 3-arc second point spacing – approximately 100- by 100-meter spacing in x and y – with geographic coordinates on the World Geodetic System (WGS) 72 or WGS 84 horizontal datum and **NGVD 29 vertical datum**. They provide coverage in 1- by 1-degree blocks. They are formatted to USGS specifications from NIMA's DTED. Coverage of the entire United States is complete.

- **Alaska** has several other types of DEMs, with point spacing that adjusts for the convergence of meridians at northern latitudes.

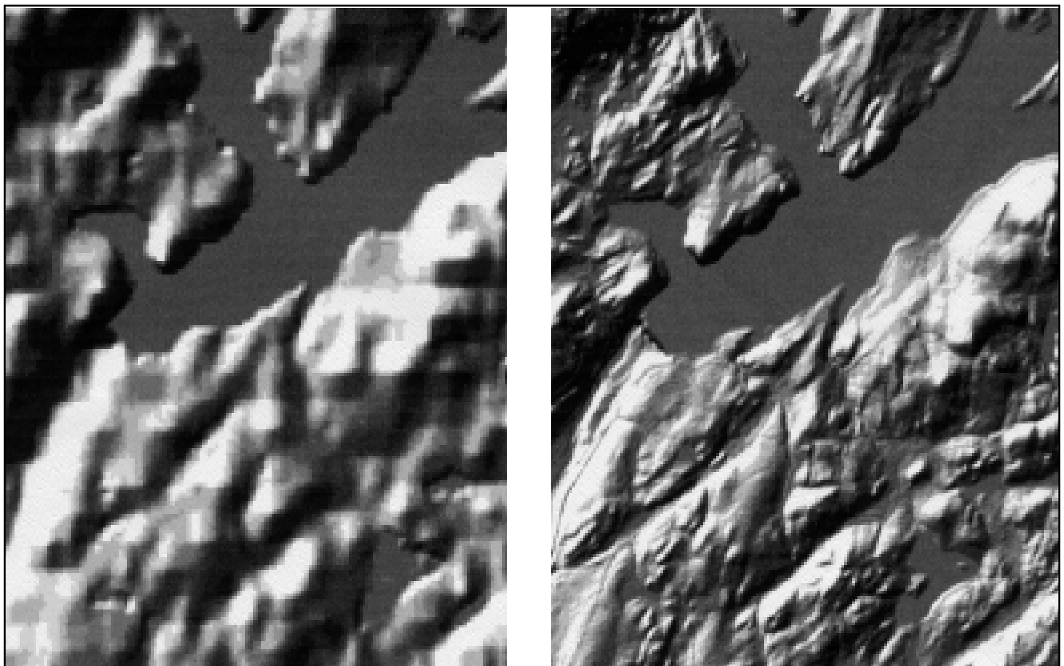
8.9.2 USGS DEM Levels and Their Vertical Accuracy

DEMs are classified into one of three levels of quality. There are varying methods of data collection and degrees of editing available for DEM data. All USGS DEMs are tested and assigned a vertical root mean square error (RMSE).

- **Level 1 DEM** data are created by automated stereo correlation or manual profiling from aerial photographs such as photos from the

National High Altitude Photography (NHAP) program, initiated in 1980, which produced images at a scale of 1:80,000, and the follow-on National Aerial Photography Program (NAPP), initiated in 1987, which produces images at a scale of 1:40,000. Level 1 30-minute DEMs may be derived or resampled from Level 1 7.5-minute DEMs. The Level 1 7.5-minute DEMs meet the minimum accuracy requirements to support production of Digital Orthophoto Quarter-quads (DOQs) compiled at a scale of 1:12,000.

- **Level 2 DEMs** are created from 1:24,0000-scale contours for the conterminous U.S. and from 1:63,000-scale contours in Alaska. Level 2 DEMs are elevation data sets that have been processed or smoothed for consistency and edited to remove identifiable systematic errors.



DEM Level 1 *DEM Level 2*

Figure 29 Comparison of Level 1 and Level 2 DEMs

DEM data derived from hypsographic and hydrographic data digitizing, either photogrammetrically or from existing maps, are entered into the Level 2 category after review on a DEM editing system. An RMSE of one-half contour interval is the maximum permitted with no errors greater than one contour interval. The accuracy and data spacing are intended to support computer applications that analyze hypsographic features to a level of detail similar to manual interpolations of information from printed source maps.

- **Level 3 DEM** data are created from DLGs that have been vertically integrated with all categories of hypsography, hydrography, ridge line, break line, drain files, and all survey control networks. They require a system of logic incorporated into the software interpolation algorithms that clearly differentiates and correctly interpolates between the various types of terrain, data densities, and data distribution. An RMSE of one-third of the contour interval is the maximum permitted, with no errors greater than two-thirds contour interval.

Level 2 and Level 3 DEM data derived from contours generally represent slope more accurately than Level 1 DEM data. The USGS does not currently produce Level-3 DEM data.

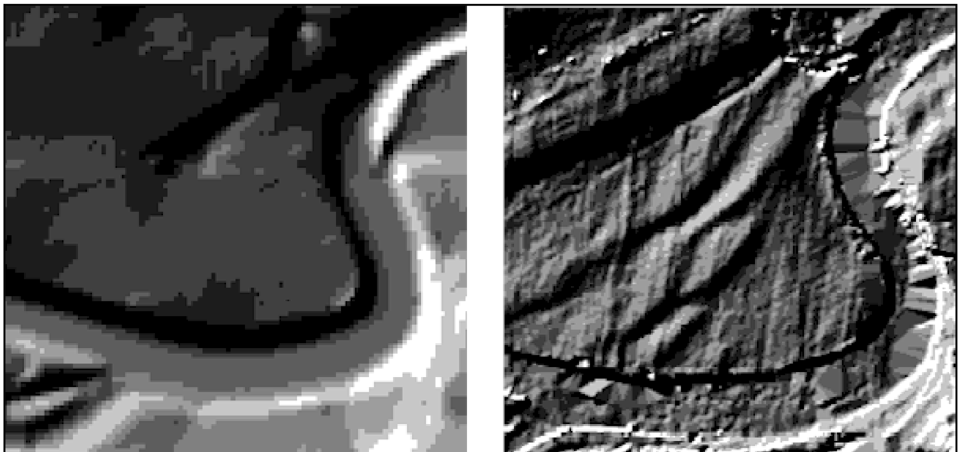
8.10 Photogrammetrically Generated DEMs

GPS technology has dramatically impacted the photogrammetry profession, because airborne GPS and Inertial Measuring Units (IMUs) are now used for navigation in the aerial photography process, and they greatly simplify the aerial triangulation process required for photogrammetric mapping, contouring, and/or DEM generation. However, to achieve 6" accuracy for DEMs, the photogrammetric mapping aircraft needs to fly at a very low altitude to acquire large-scale photography, and production costs increase significantly with increased requirements for vertical accuracy. DEMs available today from USGS do not satisfy many modern requirements for DEMs, as summarized in Tables 1 through 5 in Chapter 3 of this report, but they do represent what is practical and affordable using state-of-the-art photogrammetric techniques.

Detailed procedures for DEM extraction, editing, matching, and quality control are detailed in Chapter 6 of *Digital Photogrammetry, An Addendum to the Manual of Photogrammetry*, published in 1996 by the American Society for Photogrammetry and Remote Sensing (ASPRS). Page 140 explains fundamental problems with photogrammetric compilation of DEMs in vegetated areas, and the potential of airborne laser scanners (see LIDAR below) to solve such problems.

8.11 LIDAR-Generated DEMs

Figure 30 Comparison of a Level 2 and LIDAR DEMs



The Level 2 DEM was provided by the New York State Department of Environmental Conservation (NYSDEC). The LIDAR DEM, provided by PAR Government Systems under contact to NYSDEC, was produced by EagleScan Inc., using the Digital Airborne Topographic Imaging System (DATIS).

A recent article by DeLoach[27] discusses photogrammetry as well as LIDAR and IFSAR, which have recently become viable alternatives for generating DEMs. Airborne LIDAR uses an aircraft equipped with airborne GPS and Inerrtial Motion Unit (IMU) sensors for 3-D positioning and orientation in airspace, plus a laser system designed to measure the 3-D coordinates of passive targets. The laser measures the range to the ground surface (or targets), and, when combined with the position and orientation of the aircraft, yields the 3-D positions of the targets, accurate to approximately 15 cm (6 inches) at flying heights of 6,000 feet. LIDAR data are typically three or more times more dense than photogrammetrically captured elevation data, and they provide an ideal DEM for the rectification of digital orthophoto images. LIDAR yields vertical accuracy of 1-2 feet from flying heights of 20,000 feet. The better LIDAR systems can capture both the first and last returns from each laser pulse, providing both tree canopy elevations and ground elevations.

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[27] DeLoach, Stephen, "Photogrammetry: A Revolution in Technology", ***Professional Surveyor,*** March 1998, pp. 8-14.

When produced for large areas (e.g., an entire state), the LIDAR DEMs cost approximately $500 per square mile for unrestricted use. They are far superior to either Level 1 or Level 2 DEMs and are also more costly. The cost of Level 2 DEMs varies between $10 and $100 per square mile, depending upon how costs are computed, e.g., whether or not the cost of photogrammetric contouring and hypsographic and hydrographic DLG production is included.

The estimated cost of LIDAR DEMs nationwide would be approximately $2 billion, but the estimated benefits would be even greater, as indicated in Table 22.

Whereas the prior DEM comparisons (Figure 29) show the superiority of Level 2 DEMs compared with Level 1 DEMs, Figure 30 shows the superiority of LIDAR-generated DEMs compared with Level 2 DEMs when zoomed in. IFSAR DEMs, explained in the next section, lie somewhere between the two extremes shown in Figure 30.

8.12 IFSAR-Generated DEMs

Airborne IFSAR is similar to airborne LIDAR, except that IFSAR uses radar interferometry instead of lasers to measure the 3-D coordinate of passive targets and can do so in all weather conditions, including total cloud cover. IFSAR accuracy is approximately 1-2 meters when flown at an elevation of 20,000 feet, approximately 3-meters when flown at 40,000 feet. A limited number of LIDAR cross strips can be used to improve the accuracy of the IFSAR DEMs to a few feet.

IFSAR DEMs cost between 1/10th and 1/20th as much as LIDAR DEMs, i.e., between $25 and $50 per square mile when mass produced over large areas. ***With minimal developmental activity, it would be possible to fly IFSAR and LIDAR sensors concurrently in the same mapping aircraft to combine the advantages of each sensor.***

IFSAR DEMs (flown with north-south flight lines, for example) can be significantly improved with a few LIDAR cross-strips (flown with east-west flight lines) to correct systematic errors in the IFSAR data.