The NGS Gravity Program: Socio-Economic Benefits and Geospatial Applications

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Contents

Tables

Figures

Text Boxes

Preface

The National Geodetic Survey (NGS) has made it considerably easier to determine accurate "orthometric" heights, roughly equivalent to elevations "above sea level", based upon Global Positioning System (GPS) measurements. Knowledge of the gravity field is required to connect GPS-derived heights to sea level. These orthometric heights are vital for understanding the direction water will flow in many applications and for scientific uses.

The 1998 National Height Modernization Study[1] documented many opportunities for improving heights in the National Spatial Reference System using GPS measurements and the benefits that could be obtained. In 2001, earmarked funding began for state-by-state evolution of a National Height Modernization Program. In 2010 the Gravity for the Redefinition of the American Vertical Datum (GRAV-D) Program began aerial gravity surveys that will form the core of a new geopotential (containing what was historically called a "vertical") datum in 2022.

In 2006, the National Ocean Service held a Valuation Workshop which led to plans to regularly prepare socio-economic studies for its programs. As part of that effort, following the NGS 10-year plan, the NGS Strategic Plan for 2019-2023 called for NGS to promote socio-economic awareness by engaging: "in an analysis of the socio-economic benefits of our products and services on a 10-year cycle as a means of updating and improving our knowledge base and evaluating the benefits of our programs."[2] This is the fourth such study for NGS which the author has been privileged to engage in and the second for ARCBridge Consulting and Training, Inc.

ARCBridge Consulting and Training and Irv Leveson wish to give special thanks to Vicki Childers who oversaw the project and to Jessica Doten, Maureen Green, Jeffery Johnson, Sherri Watkins, and Derek van Westrum who contributed to oversight discussions. Christine Gallagher, Julian Inasi and Steve Vogel provided valuable information on NGS activities. We greatly appreciate the time and insights of those who were interviewed, including Kevin Ahlgren, Dana Caccamise, Bernard Coakley, Trevor Greening, Richard Hassler, Gregory A. Helmer, Larry Hothem, Jeffery Johnson, Kevin Kelly, Laura Rear-McLaughlin, Dan Roman, Paul Rooney, Dru Smith, Yan-Ming Wang and Derek van Westrum. The comments on the report by Vicki Childers, Jeffrey Johnson, Dan Roman, Dru Smith and Derek van Westrum are especially appreciated.

Priti Mathur managed the project and Gia Meli provided research assistance. Responsibility for the content lies with Irv Leveson, the technical lead, who conducted the analyses and prepared the report.

Cover map: NGS graph of the continental bias and tilt of the NAVD 88 H=0 surface across CONUS as implied by the latest NGS experimental geoid model based on improved gravity data

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[1] Dewberry & Davis and Psomas & Associates, *National Height Modernization Study: Report to Congress*, Washington, DC: National Oceanic and Atmospheric Administration, National Geodetic Survey, June 1998 https://www.ngs.noaa.gov/PUBS_LIB/1998heightmodstudy.pdf

[2] U.S. National Oceanic and Atmospheric Administration, National Geodetic Survey, *National Geodetic Survey Strategic Plan, 2019-2023*, 2019, p.5 https://www.ngs.noaa.gov/web/about_ngs/info/mission-strategic-planning.shtml

Scaling the Heights: The NGS Gravity Program Socio-Economic Study

Summary

The Role of the National Geodetic Survey

The National Geodetic Survey is part of the U.S. National Oceanic and Atmospheric Administration (NOAA), an agency of the U.S. Department of Commerce, under its National Ocean Service (NOS).

"Within NOS, NOAA's National Geodetic Survey (NGS) has a federal mandate to provide accurate positioning, including heights, to all federal non-military mapping activities in the U.S.A."[3]

Text Box S1. What Is Geodesy?

"Geodesy is the science of accurately measuring and understanding three fundamental properties of the Earth: its geometric shape, its gravity field, and its orientation in space, as well as the changes of these properties with time."

Source: https://geodesy.noaa.gov/INFO/geodesy.shtml

The National Geodetic Survey (NGS) "defines, maintains, and provides access to the National Spatial Reference System (NSRS)— a consistent coordinate system that defines latitude, longitude, height, scale, gravity, and orientation throughout the United States."[4'5]

The NGS Gravity Program Will Improve Orthometric Heights

The National Geodetic Survey Gravity Program is an ongoing effort by NGS to collect, research, understand and use information about the gravity field of the Earth for the fulfillment of its mission. A primary goal of the NGS Gravity Program is to model and monitor Earth's geoid, a geopotential datum which approximates mean sea level, to serve as a zero-reference surface for all heights in the nation. Orthometric heights take into account gravity and are roughly equivalent to elevations "above sea level."

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[3] National Geodetic Survey, "GRAV-D," https://www.ngs.noaa.gov/GRAV-D/science.shtml

[4] U.S. National Oceanic and Atmospheric Administration, National Geodetic Survey, "NOAA Manages the National Spatial Reference System," https://www.ngs.noaa.gov/INFO/OnePagers/NSRSOnePager.pdf

[5] U.S. National Oceanic and Atmospheric Administration, National Geodetic Survey, "NOAA Manages the National Spatial Reference System," https://www.ngs.noaa.gov/INFO/OnePagers/NSRSOnePager.pdf

NGS' new geoid model, developed within the Gravity Program, part of a modernized National Spatial Reference System slated for release in 2022, will allow users to quickly and accurately determine orthometric heights via GPS (and Global Navigation Satellite Systems - GNSS - in general) measurements. Knowledge of the gravity field is required to connect GPS-derived heights to sea level. The Gravity Program will provide comprehensive data for the U.S. and its territories in 2022, with updates occurring as needed to maintain NSRS accuracy requirements.

Knowing orthometric heights is essential for determining the direction water will flow. Orthometric height information is used in a wide range of commercial, scientific, resource and environmental applications. Examples of critical applications include floodplain management and local sea level measurement in coastal zones. This study seeks to explore and measure many of those benefits to provide information for public and private decision-makers and users of the NGS data.

Improvements in measurement are needed because traditional orthometric height measurement with surveying techniques is expensive, relies upon height information on physical bench marks that are rarely checked for accuracy, is not accurate in hard-to-reach areas where bench marks are not available and cannot be used for coverage of large geographic areas.

In many locations, height information has become outdated over time. The greatest need for civilian uses exists in:

- Terrain that is mountainous so ground-based techniques cannot cover many areas. Few have been previously measured from the air
- Low lying coastal areas which are subject to flooding from hurricanes and sea level rise
- Topography of the continental shelf, which is not well-measured and can influence the extent to which winds push water onshore
- Flood plains for which measures of height and therefore water flow have not been adequate for regulating construction, providing warnings and insurance
- Areas that need updating and monitoring because of earthquake activity, post-glacial rebound (uplift), subsidence of land due to withdrawal of water, and/or that have been affected by melting of glaciers
- Areas with insufficient numbers of bench marks or where bench marks have been damaged, removed or buried due to road and infrastructure construction or natural or other events

Benefits of the NGS Gravity Program are Expected to be Very Large

The measurement of benefits has focused on reductions in costs of geospatial activities and construction projects as a whole. Under the baseline scenario for adoption, the present discounted value of economic benefits through the first 10 years of the program is $8.7 billion for the middle scenario, with a range between $4.2 and $13.3 billion between the lower and upper paths. Economic benefits would be much higher under more rapid adoption scenarios or if a lower discount rate than the OMB rate of 7% above inflation was used. The societal benefits of the program are much greater than these economic figures indicate because the program enables important safety-of-life and environmental benefits.

Many Applications Will Benefit from Improved Orthometric Heights

Text Box S2. Employment and Spending in Geospatial Industries

U.S. employment in geospatial activities is estimated at 170,000-190,000 in 2018 based on occupation data.

Direct spending on geospatial activities is estimated at $22.1-$30.4 billion in 2018.

Improved access to accurate orthometric height measurement (informed by data from the Gravity Program) will be valuable for surveying and mapping, including flood plain mapping, river and stream resource management, monitoring areas with extensive subsidence,[6,7] and post-disaster damage assessment and reconstruction. Users are expected to experience cost savings as they will have less need to perform leveling measurements. Costs of height surveys for flood insurance will be reduced. The USGS 3D elevation Program (3DEP) which maps the U.S. and its territories uses orthometric heights for validation of LiDAR data. Easier access to improved orthometric heights will make an even greater contribution to the program in the future.

The spatial environment is defined in a consistent way for maritime and terrestrial regions. Accurate orthometric heights are essential for positioning tide gauges and determining the amount of sea level rise to address flooding. The program will support comprehensive coastal and marine spatial planning through its accurate geodetic and tidal reference system. It will lead to better understanding of storm surge for coastal and terrestrial regions through the use of consistent definitions across regions. USGS also uses changes in vertical levels to monitor ground water extraction in aquifers.

Combining orthometric heights with horizontal (latitude and longitude) geodetic coordinates, along with ocean, wind and storm surge information allows the determination of how far water will go inland. Better knowledge of topography along with wind information is important for understanding offshore disturbances far out in the continental shelf that lead to storm surges inland. Elevation data is used for assessing flooding from rivers and lakes as well. The sustainability of marine fisheries will be enhanced with better knowledge of oceanic nutrient transport systems.

Benefits to navigation will come from more accurate ocean, lake and river heights, including use for determining effects of wind on oceans and coordination with terrestrial measurements. Better measures of heights of evacuation routes and levees can save lives.

Orthometric heights based upon the new NGS datum (informed by the Gravity Program) will be critical for dam and other infrastructure and construction management. Construction projects rely on orthometric heights so parts of a project fit together, to assure drainage, to avoid subsidence, and for

[6] For example, see U.S. National Oceanic and Atmospheric Administration, National Geodetic Survey, *The Effect of Modernizing the National Datums on Floodplain Mapping*, November 17, 2011 https://www.ngs.noaa.gov/PUBS_LIB/Floodplain_Pilot_Project_Final.pdf

[7] It has become necessary in some areas to examine both sea level rise and water withdrawal at the same time, since some of what appears to be sea level rise may be the result of land subsidence. John Palatiello, "Subsidence Survey Would Aid in Climate Controversy," *pobonline*, January 14, 2019 https://www.pobonline.com/articles/101556-subsidence-survey-would-aid-in-climate-controversy

other activities. Without proper orthometric height accuracy, projects can be delayed, rework required and/or facility life spans shortened. Building dams with the correct heights and raising locks and making physical improvements in them are critical because of subsidence.

Glacial melting in Alaska will be monitored more accurately. Improved orthometric heights also will be useful for interpreting seismic disturbances for scientific purposes and for determining whether projects that relied on data before seismic alteration have to be corrected. Crustal motion monitoring can determine whether Foundation CORS bench marks which provide precise geodetic measurements at their locations might have to be repaired to provide accurate data for future use.

The societal value of improved height measurement for anticipating and addressing the impacts of storms and flooding can be expected to be greater in the future to the extent there is further sea level rise and increases in the frequency or severity of extreme weather.

The Transition to GPS-Derived Orthometric Heights

The 1998 National Height Modernization Study clearly described the transition from traditional leveling that depended on triangulation and leveling networks that require line of sight to the transformation that took place with the use of GPS for orthometric heights referenced to the current datum NAVD 88.[8]

> "Until recently, NGS has relied on using conventional line-of-sight survey measurements… 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…. 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 "realtime" positioning applications. As a result, GPS has not only revolutionized the traditional civilian navigation, surveying, and mapping professions, but has spawned numerous new applications…"

The GPS system is now accompanied by evolving global satellite positioning systems of Europe, Russia and China, which along with GPS make up the Global Navigation Satellite System (GNSS). GNSS contains

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[8] Dewberry & Davis and Psomas & Associates, *National Height Modernization Study: Report to Congress*, Washington, DC: National Oceanic and Atmospheric Administration, National Geodetic Survey, June 1998, pp. xi-xii https://www.ngs.noaa.gov/PUBS_LIB/1998heightmodstudy.pdf

many more satellites and additional signals that together offer greater accuracy, reliability and availability.

Features of The NGS Gravity Program

The new geopotential datum, informed by the Gravity Program, will bring a new transformation that covers the nation and its territories more accurately, consistently and inexpensively by providing orthometric heights that can be determined for any point from a reference surface, along with data entry, processing and retrieval tools to efficiently access, process and disseminate the information.

The Gravity Program includes:[9]

1) Providing geoid heights in support of accurate, quickly available orthometric heights
2) Collecting and processing gravity data from all sources
3) Ingesting, performing quality control, processing and publishing gravity data
4) Monitoring changes to Earth's gravity field with the Geoid Monitoring Service (GeMS)

The new geopotential datum slated for release in 2022 will replace the current series of brass and concrete bench marks and rods that mark the position of individual reference points with heights based on a surface called a geoid.[10] The geoid is defined so that the potential energy due to gravity is the same at each point. Orthometric height measurement (height above the geoid) takes into account the gravitational force of the earth at each location. The new datum is called a geopotential datum (rather than a vertical datum) because it is a set of internally consistent values, each of which is related to Earth's external gravity potential field. The National Spatial Reference System consists of a geopotential datum (for height determination) and a geometric datum for 3-D positioning with respect to the satellite positioning systems. The geometric datum is tied to the high accuracy, ultra-stable NOAA Foundation CORS Network (Continuously Operating Reference Stations).

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[9] For information on the Gravity Program, see U.S. National Oceanic and Atmospheric Administration, National Geodetic Survey, *Blueprint for 2022, Part 1: Geometric Coordinates*, NOAA Technical Report NOS NGS 62, September 21, 2017 https://geodesy.noaa.gov/PUBS_LIB/NOAA_TR_NOS_NGS_0062.pdf, U.S. National Oceanic and Atmospheric Administration, National Geodetic Survey, *Blueprint for 2022, Part 2: Geopotential Coordinates*, NOAA Technical Report NOS NGS 64, November 13, 2017 https://geodesy.noaa.gov/PUBS_LIB/NOAA_TR_NOS_NGS_0064.pdf , U.S. National Oceanic and Atmospheric Administration, National Geodetic Survey, *Blueprint for 2022, Part 3: Working in the Modernized NSRS*, NOAA Technical Report NOS NGS 67, initial draft released April 25, 2019 https://geodesy.noaa.gov/PUBS_LIB/NOAA_TR_NOS_NGS_0067.pdf , Daniel R. Roman, Steven Hilla, and Kevin Choi, "Modernizing the Geometric Reference Frame," presentation at the NOAA 2017 Geospatial Summit, April 24, 2017 https://geodesy.noaa.gov/geospatial-summit/presentations.shtml and Jim Baumann, "Moving from Static Spatial Reference Systems in 2022," *esri arcuser*, Winter 2019, pp.34-37 https://www.esri.com/about/newsroom/wp-content/uploads/2019/01/Moving-Static-Spatial-Reference-Systems-2022.pdf

[10] The International Great Lakes Datum of 1985 (ILGD 85) will be updated to ILGD 2020 in 2025. NGS, "NGS Scientists Present Findings for Improving ILGD 2020," April 18, 2019 https://www.ngs.noaa.gov/web/news/igld2020.shtml

The modernized geopotential datum NAPGD2022 will be accessed through GNSS positioning, reliant upon the NOAA CORS Network and a greatly enhanced NGS Online Positioning User Service (OPUS). The Gravity Program will also provide consistent updates over time. Systematic updates have not been possible in the past.

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NGS, with its new geopotential datum, seeks to provide elevations using the reference geoid accurate to 2 cm or better in most areas. This compares with the current NAVD88 network average absolute accuracy of about 50 cm, with errors of as much as a meter or more in parts of the Continental U.S. and up to 2 m. Errors are even larger for some mountains in Alaska (see report cover and Appendix C). Differences in accuracy might include only a few centimeters of error in the local network, while the whole network is decimeters away from an accurate geoid.

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A 15-year program called Gravity for the Redefinition of the American Vertical Datum (GRAV-D) has been conducting a nationwide airborne survey to collect gravity measurements across all of the Continental U.S., Alaska, Hawaii, and all of the territorial holdings, 150 km into Canada and Mexico along the borders, and off-shore into the deep ocean. GRAV-D includes a high-resolution "snapshot" of gravity in the U.S. – predominantly through an airborne campaign, a low-resolution "movie" of gravity changes – primarily through a terrestrial campaign which mostly encompasses episodic re-visits of absolute gravity sites, and continuing measurements from gravity satellite missions such as GRACE FO.[11]

Airborne data is used for measurements between 50 km and 250 km, while surface measurements are used up to 50 km. To deal with measuring the gravity field over long wavelengths, NGS has relied on data from NASA's GRACE and Europe's GOCE satellites and now uses data from NASA's GRACE-FO satellite for wavelengths of 200-250 km or more. Data from the three sources (surface, airborne, and satellite) are blended to produce NGS' best estimate of the gravity field for our nation. The gravity field estimate based on the Gravity Program data is used to create the gravimetric geoid. The Program's Geoid Monitoring Service (GeMS) program will be monitoring changes in gravity field over time and updating the geoid as needed. This has not been possible with methods used in the past.

How Much Accuracy Will the New Datum Provide?

The accuracy of GNSS combined with geoid models is about the same as leveling at the 20-200 km level. However, leveling at those distances can take several weeks in the field and would be far costlier. The greatest cost savings are expected to come in this middle tranche.

NGS executed three Geoid Slope Validation Surveys (GSVS) as proof of concept and to estimate orthometric height accuracy improvement as a result of the GRAV-D program. GSVSs were conducted in 2011 in Texas, 2014 in Iowa and 2017 in Colorado to evaluate height improvement brought by the GRAV-D data in areas of increasingly rough terrain. A GSVS provides an independent estimate of the geoid slope, which is then compared with two geoid models, one with and one without airborne data.

[11] https://www.ngs.noaa.gov/GRAV-D/

The Texas and Iowa surveys have confirmed the ability of GRAV-D to obtain 1-2 cm geoid accuracy. Results from the Colorado survey are not completed but the difference will be larger because of the mountains.

Maps of areas with substantial subsidence or uplift are shown in Appendix B. Appendix C shows expected changes in orthometric heights with improved measurement across CONUS. These include both errors in the local network and errors in the positions of the networks.

As it did two decades ago, improved orthometric height measurement is expected to result in far reaching changes in what are now more evolved and diverse geospatial industries and customers. This involves not only realignment of use of technologies and resources, but also evolution of new applications and methods which transcend what can reliably be anticipated in advance.

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Objectives of this Study

The connection between orthometric height data to support geodetic control needs and socio-economic outcomes has not been broadly examined since the 1998 Height Modernization Study[12] and benefits are not widely understood. Benefits of the orthometric height data to be provided as a result of the Gravity Program potentially can be as great or greater and more far-reaching than the 1998 data because of much greater accuracy, availability and lower cost.

The value of information on socio-economic benefits of the Gravity Program is in:

- Improving NGS' understanding of customers, applications and requirements of the program.
- Informing decisions about the allocation of resources among programs.
- Advancing recognition of the applications and contributions of the program among users and decision-makers.

The study seeks answers to the following five questions:

1. Who benefits from NOAA's NGS Gravity Program?
2. What is the nature of these benefits (how are these benefits accrued)?
3. What methodology is appropriate to best estimate the value of NGS Gravity Program services to these users?
4. What are the *preliminary* estimates of the distinct value for NGS Gravity Program services?
5. How many jobs do NGS Gravity Program products and services support?

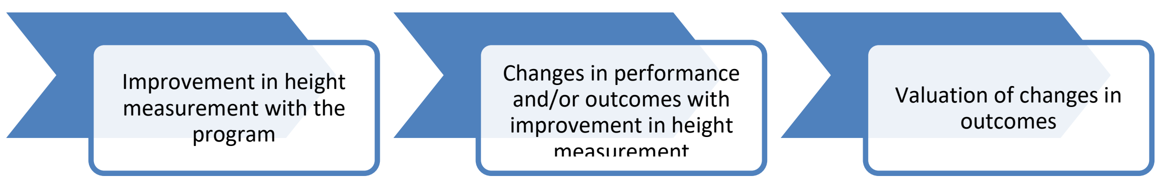
[12] Dewberry & Davis and Psomas & Associates, *National Height Modernization Study: Report to Congress*, Washington, DC: National Oceanic and Atmospheric Administration, National Geodetic Survey, June 1998 https://www.ngs.noaa.gov/PUBS_LIB/1998heightmodstudy.pdf

Data available for benefit measurement are at an aggregate level. Consequently, for the purpose of measuring benefits, the Gravity Program has been defined broadly to include both the new geopotential datum slated for release in 2022 and the NGS services that make it operational for users.

This is a scoping study which seeks to provide rough orders of magnitude estimates of benefits. Benefit estimates are necessarily very preliminary because: 1) the program is not yet operational, so actual outcomes cannot be measured, 2) there can be many more types of benefits than the study can consider, and 3) there are many limitations to the availability and suitability of data. The analysis is for the civilian U.S., including its territories, and does not include benefits to other nations or to global measurement.

Figure S1 illustrates the process of benefit determination.

Figure S1. Benefit Determination



Measurement of Benefits

Conceptually, there are many possible measures of benefits. Substantial cost savings can occur not only in data collection in the field but also in processing the data in the office and in NGS. Savings in equipment and personnel also may come from better scheduling, including benefits to other parts of a construction project and to agriculture and shipping. Greater accuracy and reduced uncertainty about heights can result in less rework or longer use of infrastructure projects. The primary focus in this study is on cost savings and avoided costs from greater accuracy and availability of information than in the past.

The analysis incorporates information from the footprint analyses, examination of the nature of benefits, review of existing studies and analyses from NGS, expert opinion, external data, and economic and statistical methods whose application depends on the nature of the data.

Benefits are incremental. They are measured by comparison with outcomes that would be expected in the absence of the program.

Benefits are incremental. They are measured by comparison with outcomes that would be expected in the absence of the program. Rough adjustments are made where appropriate to allow for benefits attributable to the use of alternative technologies. Benefits are gross in that they do not deduct any differential costs to users for taking advantage of the new geopotential datum such as for equipment, software, databases and training.

A economic multiplier of 1.4 which is low compared to many other studies is incorporated to conservatively include impacts on other parts of the economy. Multiplier effects include influences on supplying and customer sectors and effects of additional spending by employees.

Benefits are scaled to the 2019 economy's purchasing power and output. It will take many years for the new geopotential datum to be adopted widely. Scenarios are used in estimating future benefits, informed by judgements about the historical pace of adopting a new datum and market considerations.

Present discounted values of streams of future economic benefits over 10 years are calculated for each of the scenarios to provide total measures of the value of the NGS Gravity Program through improvement in orthometric heights.

Ranges are used to reflect uncertainty in the estimates. Uncertainty also is represented by alternative scenarios for the evolution of benefits and by the use of alternative discount rates in discounting future benefits.

A number of possible effects on jobs are discussed and their net effect is considered.

Standard economic methods are available to place values on lives saved and injuries. These are applied for two applications for which data is available.

One can speculate as to whether advances in measurement will result in percentage gains that are smaller or larger than those of the past. The present study estimates smaller percentage improvements in benefits than found in the 1998 National Height Modernization Study, erring on the side of conservatism in the absence of more robust information or the ability to measure the program in operation.

Potential Benefit Estimates

Potential benefits are those that would be expected at 100% adoption. The analysis of scenarios for rates of adoption through 10 years covers a period before100% potential is reached. Two methods are used to estimate potential annual benefits. Categories within a method do not overlap but there is some overlap between methods.

- **Method 1** applies 50% to the value of spending on geospatial activities that was derived by building on occupation data. The 50% reduction is used to allow for work done using other technologies, work done at distances at which geoids do not provide an advantage, and work in the included occupations that is unrelated to orthometric height measurement. An estimate of savings with improved orthometric heights is applied to the resulting value. An allowance is made for greater benefit with the final Gravity Program data and especially for effects of improved orthometric heights on reduced non-geospatial project costs, including construction costs, reduction in rework and/or repairs and longer lives of buildings and infrastructure.

Estimates of some subcategories are shown for illustrative purposes where information was available. These are independent of the overall Method 1 estimate and are not combined into a total. Estimates are made for reduced costs of long line leveling and for FEMA floodplain mapping under the National Flood Insurance Program. These replace the estimates in the 2009 study of benefits of CORS and GRAV-D. In addition, a rough estimate of the contribution of improved orthometric heights derived from the Gravity Program to benefits of the NWS river and flood forecasts is made based on updates of an earlier National Hydraulic Warning Council study.

- **Method 2** is a hybrid that does add its components. It updates benefit estimates for reduced costs of high accuracy digital elevation models (DEMs) from the National Height Elevation Assessment conducted by Dewberry and reported in 2012. In that study accuracy requirements were examined for many use cases. The present estimate replaces the 2012 study's value for agriculture and adds an estimate for marine navigation, using information that is not limited to DEMS.[13] Estimates are also made for the PORTS® Program and for inland waterways. Estimates are included where possible and do not constitute a complete list of applications.

The estimates are shown in Table S1. Method 1 produces an estimate of potential direct economic benefits of the NGS Gravity Program based on the 2019 economy of $2.55-$6.05 billion per year, with a midpoint of $4.30 per year. The Method 2 estimate $1.72-$3.23 billion per year, with a midpoint of $2.48 billion per year.

Indirect and induced effects on the rest of the economy are included by adding a multiplier of 1.4 to obtain "full" potential benefits. Applying the economic multiplier to potential economic benefits of $1.85-$4.30 billion per year with Estimate 1 yields full potential economic benefit of $2.55-$6.05 billion per year, with a midpoint of $4.30 billion. With Method 2 the multiplied range is $2.41-$4.52 billion per year with a midpoint of $3.47 billion.

Applying the economic multiplier to potential economic benefits of $1.85-$4.30 billion per year with Estimate 1 yields full potential economic benefit of $2.55-$6.05 billion per year, with a midpoint of $4.30 billion.

The Method 1 estimate is preferred because it includes many more applications than Method 2.

The economic benefit estimates do not include possible reduced damage from floods and storms with better height information. They also do not include the contribution to the value of infrastructure projects above their cost.

[13] The agriculture and maritime sectors made up the great majority of the benefits from the introduction of GPS estimated in the 1998 National Height Modernization Study.

Table S1. Summary of Potential Direct Annual Economic Benefits of the NGS Gravity Program to the U.S. at 100% Adoption Based on the 2019 Economy

Sector or Application	Annual Benefit	Basis	Comments
Method 1. Geospatial Activities Total	**$2.55-$6.05 billion**	Experience with the use of geoids applied to geospatial spending, which was estimated based on occupation data, plus an allowance for other impacts on project end costs and lives	Preferred over Method 2 because it is much more comprehensive.
Long line leveling	$65.0-$97.5 million	The amount of long line leveling is assumed to be half as great as in the 2009 study	The amount is less because of costs and use of available geoids
FEMA NFIP floodplain management	$110-$180 million	Includes $3-$6 million in savings for elevation mapping and $50-$120 million from use of the maps	Allows for insurance becoming voluntary and more costly for structures with greater vulnerability
Benefits through NWS river and flood forecasts	$360-$804 million	Assumed percentage contribution to values from update of National Hydrologic Warning Council study	Includes reservoir optimization, snow melt and other long term flood events, short term forecasts that allowed time for responses and use in the AHPC
Method 2. Sum of Components Total	**$1.72-$3.23 billion**	Sum of estimate for DEMs, agriculture and marine transportation	
Improved Digital Elevation Maps based on Dewberry (2012)	$934.4 million-$1.402 billion	Based on a percentage of benefits of various enhancements to Digital Elevation Maps	The estimate based on the 2012 Dewberry study is relied on over the 1998 study because the data is more current and complete. The estimate uses the lower value.
Addendum: Updated total of 5 applications from 1998 study	*$400-$800 million*	*Cost reduction from use of high accuracy Digital Elevation Models from the 1998 National Height Modernization Study, updated by change in nominal GDP*	*Includes a range of activities of USACE, FEMA, NWS and several other federal agencies along with local planning and stormwater management efforts*
Agriculture	$700 million-$1.65 billion	Estimated at half of the updated value of GPS for precision farming. Excludes benefit for DEMs which are counted separately.	The estimate does not include use of techniques besides auto-guidance or crops other than grains.
Marine transportation – total			
The PORTS® Program	$16.7-$45.8 million	Based on hypothetical extension of the program to 175 ports	Reflects the preponderance of benefits in the 2016 study of the PORTS® program coming from greater cargo carriage with increased hull clearance
Inland waterways	$27.6-$66.0 million	Illustrative indication of possible order of magnitude	Based on National Waterways Foundation abandonment scenario

Economic Benefits Scenarios

Economic benefits of improved orthometric heights derived from the Gravity Program, including multiplier effects on the rest of the economy, are illustrated in alternative scenarios based on percentages of potential benefits over 10 years from 2023-2032. The scenarios are in year 2019 purchasing power applied to future levels of output based on Congressional Budget Office projections. The scenarios do not go out further because there is too much uncertainty about development of complementary and alternative technologies and other factors. Percentage adoption refers to the percent of the value of benefits and not to the percentage of people using the system.

Scenarios represent dollar values of benefits above what would be expected in the absence of the NGS Gravity Program. The three main scenarios: “baseline,” “fast out of the gate,” and “continuing rapid buildup” are described below. Table S2 shows the middle values of the Method 1 and Method 2 scenarios.

Baseline. Under the baseline scenario, adoption takes place gradually as upgraded skills and applications are phased in and as the need for legislation and for users to maintain historical comparability constrain adoption. Adoption reaches 25% in the 6th year and 50% in the 10th year.

Fast out of the gate. Rapid adoption takes place among high value projects and more skilled users. It is facilitated by efforts to take advantage of the years until the improved orthometric heights become available. Adoption as a percent of program benefits reaches 35% in the 6th year and 62% in the 10th year.

Continuing rapid buildup in use. Recognition of benefits of the program builds over time and skills develop to take advantage of it. Incorporation of the new geoids by equipment and software providers accelerates adoption but resulting benefits are tempered by some inappropriate “push button” use.

The middle values of the scenarios are shown in Table S2. The full ranges are in Tables 17 and 18.

Table S2. Method 1 and 2 Scenario Middle Values of Annual Economic Benefits of the Gravity Program
(billions of 2019 dollars)

Year	Scenario					
	Method 1			Method 2		
	Baseline	Fast Out of the Gate	Continuing Rapid Buildup	Baseline	Fast Out of the Gate	Continuing Rapid Buildup
2020	0	0	0	0	0	0
2021	0	0	0	0	0	0
2022	0	0	0	0	0	0
2023	0.14	0.23	0.19	0.08	0.14	0.11
2024	0.33	0.52	0.42	0.20	0.31	0.25
2025	0.53	0.82	0.77	0.31	0.48	0.46
2026	0.73	1.12	1.07	0.43	0.67	0.64
2027	0.99	1.44	1.39	0.59	0.85	0.83
2028	1.26	1.77	1.52	1.05	1.47	1.26
2029	1.60	2.16	1.96	0.95	1.28	1.16
2030	1.90	2.52	2.37	1.13	1.50	1.40
2031	2.31	2.93	2.78	1.37	1.74	1.65
2032	2.67	3.31	3.20	2.22	2.75	2.66

Note: Includes multiplier effects.

Present Discounted Values of Economic Benefits

Future values of benefits were discounted to 2019. Discounting alternatively can be interpreted as reflecting preferences for a dollar today over receipt of that dollar later, the cost of borrowing funds or returns on alternative investments. The discount rate is analogous to the return on investments *above* inflation. Discounted benefits are in 2019 dollars.

The present discounted value (PDV) of benefits with a 7% discount rate is $8.71 billion under the middle baseline scenario with Method 1 – which is preferred to Method 2 because its coverage of applications is much more comprehensive (Table S3).

> The present discounted value (PDV) of benefits with a 7% discount rate is $8.71 billion under the middle baseline scenario with Method 1 – which is preferred to Method 2 because its coverage of applications is more comprehensive.….
>
> Benefits would be higher with more rapid adoption. The PDV for the Method 1 middle “fast out of the gate” scenario, with a 7% discount rate is $11.91 billion. In the continuing rapid buildup scenario it is $11.04 billion.

With Method 2, the middle baseline scenario PDV at 7% is $3.99 billion.

Benefits would be higher with more rapid adoption. The PDV for the Method 1 middle "fast out of the gate" scenario with a 7% discount rate is $11.91 billion. In the continuing rapid buildup scenario, it is $11.04 billion.

The 7% discount rate that was promulgated by OMB decades ago which was used for the main calculations of present values of future benefits is much higher than the current "real rate of return" on long term bonds and the real rate expected in the next decade. Implications of 3% and 5% discount rates are shown (Table S3). Use of alternative discount rates would result in much larger discounted benefit values, on the order of 20% higher with a 5% discount rate compared with a 7% rate and 50% higher with a 3% discount rate.

Table S3. Present Discounted Values of Gravity Program Benefits for Alternative Scenarios and Discount Rates
(billions of 2019 dollars)

	Scenarios and Their Ranges of Estimates								
	Lower			Middle			Upper		
	Baseline	Fast Out of the Gate	Continuing rapid buildup	Baseline	Fast Out of the Gate	Continuing rapid buildup	Baseline	Fast Out of the Gate	Continuing rapid buildup
Method 1									
PDV 3%	$5.65	$7.40	$6.98	$9.20	$12.48	$11.60	$12.78	$17.35	$16.12
PDV 5%	$4.65	$6.11	$5.76	$7.57	$10.31	$9.57	$10.52	$14.33	$13.30
PDV 7%	$3.85	$5.07	$4.78	**$6.26**	**$8.56**	**$7.94**	$8.70	$11.90	$11.04
Method 2									
PDV 3%	$3.73	$5.73	$5.33	$6.12	$8.26	$7.68	$7.99	$10.79	$10.03
PDV 5%	$3.07	$4.72	$4.38	$5.02	$6.80	$6.31	$6.55	$8.89	$8.24
PDV 7%	$2.54	$3.91	$3.62	**$4.14**	**$5.63**	**$5.22**	$5.41	$7.36	$6.82

Note: Includes multiplier effects.

The ranges around the economic benefit numbers are wide, reflecting uncertainty and limited information for a program whose operation is years away.

It is suggested that there will be fewer jobs in geospatial occupations, but more jobs at higher skill levels. However, there could be more jobs in other sectors, at least partially offsetting the loss of direct geospatial jobs. The net effect of all of the changes on payroll could be positive or negative.

Reduced fatalities and injuries could be substantial with improved orthometric heights. I the absence of more extensive information, estimates were made for NWS River and Flood Forecasts and the PORTS® program for which there was a basis in available studies. These are in Appendix E. Environmental benefits were not estimated because of data limitations. These also are not included in the economic benefit estimates, and their societal values could be very large.

Some Suggestions for Monitoring, Data Collection and Research

Several government agencies previously collaborated to produce an analysis of the effects of modernizing the national datums for floodplain mapping in a 2011 report to demonstrate how an improved datum could be used.[14] A new version for floodplain mapping is underway led by NASA. Similar studies for other applications would be useful. It would be beneficial if potential socioeconomic impacts were examined within or in conjunction with such efforts

When improved orthometric heights derived from the Gravity Program are in operation it will be possible to develop a more accurate assessment of socioeconomic outcomes and valuation of benefits. It also would be useful to have a socio-economic study of forthcoming NGS improvements in the NSRS overall, building on present efforts.

NGS continually makes extensive efforts at outreach to user communities. However, there is still a large unmet need for understanding of the Gravity Program and the new datums. Additional means of outreach might be considered, including 1) capability for consolidated online search of materials on the NGS Web site by topic which is independent of the type of material (report, article, Webinar, etc.) and also includes search by date, to make the vast amount of material even more accessible, and 2) more writing for less sophisticated professional audiences to encourage upgrading of skills and to help provide a knowledge base from which more technical upgrading can advance. It is understood that NGS technical staff are fully occupied with the Gravity Program and their other efforts, but it would be useful if sufficient resources in NGS and academic partners could be available at an early date for this purpose. Much explanatory information can also come from the private sector and user organizations.

NGS will have to continue to closely monitor rapidly evolving technologies and applications and their impact on its methods and processes even as it seeks to complete and refine its present efforts and provide updates. Work on the next set of improvements would have to start well before 2032 since the lead times required to transform or adapt complex processes can be great. NGS fully recognizes this and requires continuing resources after the new datum is in operation to prepare for future changes.

Large adaptations are required for users to take advantage of the improved orthometric heights and rapidly changing technologies, not only to effectively apply the methods, but also so use of the data will be fully effective. In a 2007 study of survey science in the decade 2007-2017, the U.S. Geological Survey concluded:

> "Rapid advances in the technology of data collection have made it possible for scientists to describe complex systems in multiple dimensions in space and time….Therefore, the challenge now is to synthesize this information with models and decision-support tools that can be used to communicate the consequences of human actions to decision makers and resource managers in a language that crosses disciplinary boundaries."[15]

The need to effectively transition from measurement to decision-making has never been greater than it is today, and NGS support for use of improved orthometric heights derived from the Gravity Program will help others to take the next steps.

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[14] Youngman, Monica, *et. al.*, *The Effect of Modernizing the National Datums on Floodplain Mapping*, National Oceanic and Atmospheric Administration, National Research Council, November 17, 2011 https://www.ngs.noaa.gov/PUBS_LIB/Floodplain_Pilot_Project_Final.pdf

[15] U.S. Geological Survey, *U.S. Geological Survey Science in the Next Decade 2007-2017*, Circular 1309, p.45 https://pubs.usgs.gov/circ/2007/1309/pdf/C1309Text_508.pdf

Scaling the Heights: The NGS Gravity Program Socio-Economic Study

The NGS Gravity Program

The geopotential datum will provide much more accurate measures of orthometric heights which take into account gravity and are roughly equivalent to elevations "above sea level." Knowledge of the gravity field is required to connect GPS-derived heights to sea level. Orthometric heights are vital for understanding the direction water will flow. They are used in a wide range of commercial, resource and environmental applications and support a wide range of scientific uses. Examples of critical applications include floodplain management and local sea level measurement in coastal zones.

Ellipsoid vs. Orthometric Heights

Ellipsoid height is the straight line, vertical distance between the point of interest and the smooth, geometrically defined approximation of the earth's shape called the ellipsoid. In contrast, orthometric heights which are based on gravity are the distance along the plumb line from the point of interest to the gravimetrically defined geopotential surface called the geoid. Ellipsoid heights are referenced to the Global Navigation Satellite System (GNSS), which includes the U.S. Global Positioning System (GPS) and GNSSs of other nations such as Europe's Galileo satellite navigation system. Orthometric heights are currently obtained by reference to physical bench marks at sites at which the force of gravity is known based on NGS measurements with an absolute gravimeter. The relationship between ellipsoid and orthometric heights is depicted in Appendix A.

The Gravity Program

Overview of the Gravity Program

The NGS new geopotential datum which incorporates data from the Gravity Program will cover the nation and its territories by providing orthometric heights that can be determined for any point from a reference surface called a geoid. It will do so more accurately, consistently and inexpensively. The orthometric height measurement (height above the geoid) datum is called a geopotential datum because it combines gravity-based information with traditional heights. New tools for data entry, processing and retrieval will be introduced to enable users to efficiently access, process and disseminate the information.

The Gravity Program includes:[16]

1) Creating the geoid model to support accurate orthometric heights
2) Collecting and processing gravity data from all sources
3) Ingesting, performing quality control, processing and publishing gravity data
4) Monitoring gravity change with the Geoid Monitoring Service (GeMS)

The new geopotential datum which is part of the NGS National Spatial Reference System slated for release in 2022 will replace the current series of brass and concrete bench marks and rods that mark the position of individual reference points. Instead it will use heights based on a surface called a geoid - defined so that the potential energy due to gravity is the same at each point.[17]

The new geopotential datum which is designated as NAPGD2022 will be accessed through user submitted GNSS positions and the gravimetric geoid through a greatly enhanced NGS Online Positioning User Service (OPUS) that is supported by the NOAA CORS Network. The Gravity Program also will provide consistent updates over time. Systematic updates have not been possible in the past.

With its new geopotential datum, NGS seeks to provide elevations accurate to 2 cm or better in most areas. This compares with the current NAVD88 network average absolute accuracy of about 50 cm, with errors of as much as a meter or more in the Continental U.S. and as large as 2 m. Errors are even larger for some mountains in Alaska (see Appendix C). Differences in accuracy might include only a few centimeters of error in the local network, while the whole network is decimeters away from an accurate geoid.

Note that the height accuracy of GNSS combined with geoid models is about the same as leveling at the 20-250 km level. However, leveling in the field at these distances can take several weeks and is far more costly. The greatest cost savings in leveling are at these distances.

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[16] For information on the Gravity Program, see U.S. National Oceanic and Atmospheric Administration, National Geodetic Survey, *Blueprint for 2022, Part 1: Geometric Coordinates*, NOAA Technical Report NOS NGS 62, September 21, 2017 https://geodesy.noaa.gov/PUBS_LIB/NOAA_TR_NOS_NGS_0062.pdf, U.S. National Oceanic and Atmospheric Administration, National Geodetic Survey, *Blueprint for 2022, Part 2: Geopotential Coordinates*, NOAA Technical Report NOS NGS 64, November 13, 2017 https://geodesy.noaa.gov/PUBS_LIB/NOAA_TR_NOS_NGS_0064.pdf , U.S. National Oceanic and Atmospheric Administration, National Geodetic Survey, *Blueprint for 2022, Part 3: Working in the Modernized NSRS*, NOAA Technical Report NOS NGS 67, initial draft released April 25, 2019 https://geodesy.noaa.gov/PUBS_LIB/NOAA_TR_NOS_NGS_0067.pdf , Daniel R. Roman, Steven Hilla, and Kevin Choi, "Modernizing the Geometric Reference Frame," presentation at the NOAA 2017 Geospatial Summit, April 24, 2017 https://geodesy.noaa.gov/geospatial-summit/presentations.shtml and Jim Baumann, "Moving from Static Spatial Reference Systems in 2022," *esri arcuser*, Winter 2019, pp.34-37 https://www.esri.com/about/newsroom/wp-content/uploads/2019/01/Moving-Static-Spatial-Reference-Systems-2022.pdf

[17] In this context, potential energy is constant surface gravitational strength with a value equal to that at sea level and extended at that level under the continent.

Text Box 1. Some Definitions

(statements are adapted from language on the NGS Web site)

The NOAA CORS Network: A network of Continuously Operating Reference Stations (CORSs) that provide Global Navigation Satellite System (GNSS) data consisting of carrier phase and code range measurements in support of three dimensional positioning, meteorology, space weather, and geophysical applications throughout the United States, its territories, and a few foreign countries.

datums: Various surfaces from which "zero" is measured.

ellipsoid: A smooth mathematical surface (which resembles a squashed sphere) that is used to represent the earth's surface.

ellipsoid height: The difference in height between a topographic surface and an ellipsoid.

equipotential surface: A surface on which the force of gravity is the same at each point.

geoid: A geoid is a vertical datum at a defined height. The definition of a geoid currently adopted for the NGS Gravity Program is "the equipotential surface of the Earth's gravity field which best fits, in a least squares sense, global mean sea level."

A geoid can differ from the Gravity Program definition, for example, because altimetry is often used to define "mean sea level" in the oceans, but altimetry is not global (missing the near polar regions). As such, the fit between "global" mean sea level and the geoid is not entirely confirmable outside the United States. In another example of why a geoid may differ from the definition, there may be non-periodic changes in sea level (such as a persistent rise in sea level. If so, then "mean sea level" changes in time, and therefore the geoid should also change in time.

geoid height: The ellipsoidal height from an ellipsoidal datum to a geoid.

GRAV-D: GRAV-D is a program by the National Geodetic Survey to re-define the vertical datum of the US by 2022. The specific goal of GRAV-D is to model and monitor Earth's geoid (a surface of the gravity field, very closely related to global mean sea level) to serve as a zero reference surface for all heights in the nation.

GRAV-D consists of a high-resolution "snapshot" of gravity in the U.S. predominantly through an airborne campaign, a low-resolution "movie" of gravity changes primarily through a terrestrial campaign which mostly encompasses episodic re-visits of absolute gravity sites, and regional partnership surveys to support airborne or terrestrial surveys or to monitor local variations.

National Spatial Reference System: A consistent coordinate system that defines latitude, longitude, height, scale, gravity, and orientation throughout the United States.

Traditionally, these locations have been identified by setting a survey mark—usually a brass, bronze, or aluminum disk. Locations might also be identified by a deeply driven rod or a prominent object, such as a water tower or church spire. More recently, NGS has fostered a network of continuously operating reference stations (CORS) where each CORS includes a highly accurate receiver that continuously collects radio signals broadcast by Global Navigation Satellite System (GNSS) satellites.

Components of the NSRS include geodetic positional coordinates (latitude, longitude, and ellipsoid and orthometric heights in the official U.S. datums – currently, the North American Datum of 1983 (NAD 83) and the North American Vertical Datum of 1988 (NAVD 88)); geopotential; acceleration of gravity; deflection of the vertical; models, tools, and guidelines; the official national shoreline; Global Navigation Satellite System (GNSS) orbits; orientation, scale, and offset information relating NAD 83 to international terrestrial reference systems; and all necessary information to describe how these values change over time.

OPUS: NGS's Online Positioning User Service (OPUS) provides simplified access to high-accuracy National Spatial Reference System (NSRS) coordinates. The user uploads a GPS data file collected with a survey-grade GPS receiver and with minimal user input obtains an NSRS position via email. The resulting positions are accurate and consistent with other National Spatial Reference System users.

orthometric height: The height on the surface above the geoid.

Text Box 2. A Gravity Program Reading List

U.S. National Oceanic and Atmospheric Administration, National Geodetic Survey, *Blueprint for 2022, Part 1: Geometric Coordinates*, NOAA Technical Report NOS NGS 62, September 21, 2017 https://geodesy.noaa.gov/PUBS_LIB/NOAA_TR_NOS_NGS_0062.pdf

U.S. National Oceanic and Atmospheric Administration, National Geodetic Survey, *Blueprint for 2022, Part 2: Geopotential Coordinates*, NOAA Technical Report NOS NGS 64, November 13, 2017 https://geodesy.noaa.gov/PUBS_LIB/NOAA_TR_NOS_NGS_0064.pdf

U.S. National Oceanic and Atmospheric Administration, National Geodetic Survey, *Blueprint for 2022, Part 3: Working in the Modernized NSRS*, NOAA Technical Report NOS NGS 67, initial draft released April 25, 2019 https://geodesy.noaa.gov/PUBS_LIB/NOAA_TR_NOS_NGS_0067.pdf

Jim Baumann, "Moving from Static Spatial Reference Systems in 2022," *esri arcuser*, Winter 2019, pp.34-37 https://www.esri.com/about/newsroom/wp-content/uploads/2019/01/Moving-Static-Spatial-Reference-Systems-2022.pdf

Anthony Whitlock, "Understanding GNSS, Part 1: Ellipsoids, Datums and Realizations," *xyHT*, April 2019, pp.20-22 https://bt.e-ditionsbyfry.com/publication/?i=575152#{%22issue_id%22:575152,%22page%22:0}

Martin, Scott, "The March towards 2022," *xyHt* (September 2019), pp.33-34 http://bt.e-ditionsbyfry.com/publication/?i=610085&article_id=3453743&view=articleBrowser&ver=html5#{%22issue_id%22:610085,%22view%22:%22articleBrowser%22,%22article_id%22:%223453743%22}

Dewberry & Davis and Psomas & Associates, *National Height Modernization Study: Report to Congress*, Washington, DC: National Oceanic and Atmospheric Administration, National Geodetic Survey, June 1998 https://www.ngs.noaa.gov/PUBS_LIB/1998heightmodstudy.pdf

National Geodetic Survey 2019 Geospatial Summit slides https://geodesy.noaa.gov/geospatial-summit/index.shtml

National Geodetic Survey 2019 Geospatial Summit report (when available) https://geodesy.noaa.gov/geospatial-summit/index.shtml

Extensive information is available at https://www.ngs.noaa.gov/

The NGS Gravity Program incorporates data from a 15-year program called Gravity for the Redefinition of the American Vertical Datum (GRAV-D). GRAV-D involves a nationwide airborne survey to collect gravity measurements for the Continental U.S.. Alaska, Hawaii, and the U.S. territories, 150km into Canada and Mexico along the borders, and off-shore into the deep ocean. The nine million terrestrial gravity points are mostly over the ocean, and GRAV-D will help fill the gap. The data from GRAV-D is being combined with information from terrestrial surveys and satellites to produce the geoid.

GRAV-D consists of a high-resolution "snapshot" of gravity in the U.S. predominantly through an airborne campaign, a low-resolution "movie" of gravity changes primarily through a terrestrial campaign which mostly involves episodic re-visits of absolute gravity sites, and repeat satellite (GRACE FO or other gravity mission) gravity measurements that capture the long wavelength change in the field..[18,19]

Rationale for the Program

Traditional orthometric height measurement with surveying techniques is expensive and not accurate in hard to reach areas, where bench marks are not available, and where coverage of large geographic areas is needed. In many areas, height information has become outdated over time. The greatest need for improved orthometric height information exists in terrain that is mountainous, low lying coastal areas which are subject to flooding, flood plains, areas that need updating because of land shifts and/or loss of bench marks and topography of the outer continental shelf which is poorly measured. Maps indicating areas with significant uplift or subsidence are shown in Appendix B.

Under the present system it can be costly to attain the accuracy required for certain projects. Uncertainty about vertical positions is itself a problem. Data for construction and infrastructure projects determined with earlier datums can be found to be far less accurate than believed. When dated, incomplete and less accurate information results in large variances around orthometric heights or uncertainty about what those variances are, it is necessary for some projects to be surveyed multiple times at considerable additional costs. In some cases, projects need to be redone or problems arise later that might have been avoided.

With the Gravity Program, information will be made more accurate and consistent. "These new reference frames will be easier to access and to maintain than the current horizontal and geopotential datums NAD 83 and NAVD 88, which rely on physical survey marks that deteriorate over time."[20]

The new program will end bluebooking. Use will be facilitated through tools for data entry, processing and retrieval, best practice guidelines and training.[21]

The new geopotential datum from which orthometric heights will be derived will combine satellite data with aerial data from the Gravity for the Redefinition of the

Text Box 3. GRACE and GOCE Satellites

Introduction of GRACE data resulted an order of magnitude improvement in accuracy. Much of that improvement occurred because, unlike its predecessor: The Earth Gravitational Model 1996 (EGM), GRACE flew over the poles. GRACE resulted in accuracy in the decimeter or range. GOCE didn't fly over the poles, but it flew a lot closer to the Earth. However, it was short lived. GRACE, which lasted longer, has also ended, but a follow-on GRACE satellite is planned.

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[18] https://www.ngs.noaa.gov/GRAV-D/

[19] The Table Mountain Geophysical Observatory provides calibration of gravity meters which is essential to the GRAV-D airborne program. Because it is not possible to observe the outcomes of the Gravity Program without those calibrations, their domestic contribution is included in the estimates for the Gravity Program. The Observatory also provides measurements of deflection of the vertical. Since NGS considers these to be experimental, they are not currently part of the Gravity Program.

[20] U.S. National Oceanic and Atmospheric Administration, National Geodetic Survey, "New Datums: Replacing NAVD 88 and NAD 83," https://geodesy.noaa.gov/datums/newdatums/index.shtml

[21] Processing with private sector software and data has provided solutions with models that are internally consistent. However, these need not be aligned with the NSRS which requires updating for NGS data and geoid models.

American Vertical Datum (GRAV-D) Program[22] To deal with surface movement over long wavelengths, NGS relies on previous satellite data from NASA's GRACE and Europe's GOCE satellites and the current NASA GRACE-FO satellite for distances of 200-250 km or more. Airborne data is used for data between 50 km and 200-250 km, while surface measurements are used up to 50 km.

Geoid Slope Validation Surveys

Three Geoid Slope Validation Surveys (GSVS) were conducted by NGS to test the orthometric height accuracy of the geoid which utilizes data from the GRAV-D program. GSVS gauges height improvement from the GRAV-D airborne surveys by comparing two experimental (xGEOID) gravity models each year, one with and one without airborne data. The result is an estimate of error.

Three areas were examined: South Texas which is flat and close to the geoid, Iowa which has higher elevations and geologically interesting terrain, traversing the Midcontinent Rift System, and Colorado which has high elevation and rugged topography. The number and types of areas surveyed in the Geoid Slope Validation Surveys were constrained by NGS time and resources. The Texas and Iowa surveys have confirmed the ability of GRAV-D to obtain 1-2 cm geoid accuracy. The difference in the Colorado survey will be larger because of the mountains.

Study Objectives and Process

Orthometric heights are used by dozens of federal agencies, state and local governments and private organizations for applications ranging from water management to construction to protecting the environment. Improved orthometric heights informed by the Gravity Program can potentially have large benefits to the economy in the form of productivity improvements, cost savings and cost avoidance, and can lead to improvements in safety-of-life and the environment.

The connection between orthometric height data to support geodetic control needs and socio-economic outcomes has not been broadly examined in recent years. Moreover, benefits of the Gravity Program are not widely understood.

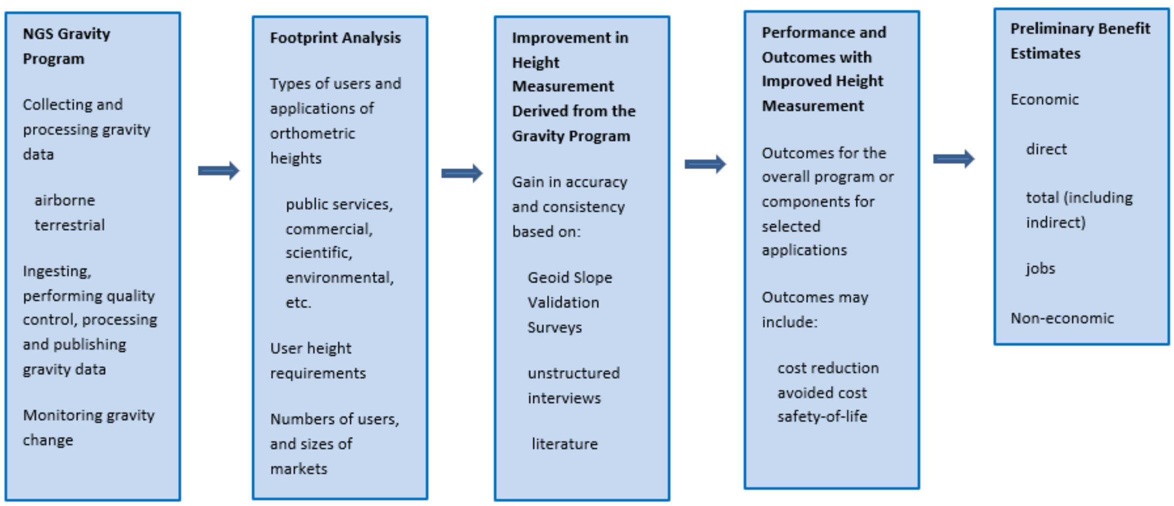
This scoping study seeks to detail and provide rough order of magnitude estimates of benefits. Because of data limitations it has been necessary to quantify broad benefits of the Gravity Program, including not

[22] Monica Youngman and Simon Holmes, "Gravity for the Redefinition of the American Vertical Datum (GRAV-D) Update," National Geodetic Survey Webinar Series, February 9, 2017 https://www.ngs.noaa.gov/web/science_edu/webinar_series/gravd-xgeoid.shtml

only those of the geopotential datum but also benefits of the NGS tools required to make the data operational for users. The analysis covers civilian applications in the U.S. and includes U.S. territories.[23,24]

The conceptual flow of the study from the Gravity Program through to socio-economic benefits is illustrated in Figure 1.

Figure 1. Study Flow for Socio-Economic Scoping Study of NGS Gravity Program



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[23] Carlson, Edward, David Doyle, and Dru Smith, "Development of Comprehensive Geodetic Vertical Datums for the United States Pacific Territories of American Samoa, Guam, and the Northern Marianas," *Surveying and Land Information Science*, 2009, pp.5-17 https://www.ngs.noaa.gov/PUBS_LIB/2009DevelopmentOfComprehensiveGeodeticVerticalDatumsForTheU.S.PacTerritoriesASGUNM)SaLIS.pdf

[24] The U.S. has a cooperation agreement with Canada and seeks to encourage and assist nations in Latin America in developing comparable measures (see Appendix D).

Footprint Analysis

Applications and beneficiaries are examined in a trade space or "footprint" analysis. The footprint analysis considers applications of orthometric heights, potential numbers of users of orthometric heights, use of NGS services, and indications of market size for users and potential ultimate beneficiaries. This analysis addresses the first two questions regarding who benefits and the nature of the benefits. It considers ways in which both direct and indirect users may benefit. The analysis brings together information from many internal and external sources.

Applications of Orthometric Height Data

Applications

The National Spatial Reference System is used at all levels of civilian government and by private organizations for applications ranging from water management to marine navigation to construction and protecting the environment.

Improved height measurement will be valuable for surveying and mapping, including flood plain mapping, river and stream resource management, monitoring areas with extensive subsidence,[25,26] and post-disaster damage assessment and reconstruction. The USGS 3D elevation Program (3DEP) which maps the U.S. and its territories uses orthometric heights for validation of LiDAR data. Improved accuracy will make an even greater contribution to the program in the future.

Text Box 5. Water Applications Are of Great Importance

Sea level changes are reflected in changes in the Earth's gravity field "…with tides and currents having almost two orders of magnitude less impact."

Improved heights will assist "…at-risk coastal areas, island regions, and other areas of the country which have an urgent and pressing need for better protection against inundation from storms, flooding and/or sea level rise."

Source: Dru A. Smith and Dan R. Roman, "How NOAA's GRAV-D Project Impacts and Contributes to NOAA Science," NOAA, April 29, 2010 , pp.2&3 https://www.ngs.noaa.gov/GRAV-D/pubs/GRAV-D_Contribution_to_NOAA_Science.pdf

Improved orthometric heights derived from the Gravity Program will be useful for dam and other infrastructure and construction management, and for interpreting seismic disturbances. Construction projects rely on orthometric heights so parts of a project fit together, to assure drainage, to avoid subsidence, and for other activities.[27] Without proper height accuracy, projects can be delayed, rework

[25] For example, see U.S. National Oceanic and Atmospheric Administration, National Geodetic Survey, *The Effect of Modernizing the National Datums on Floodplain Mapping*, November 17, 2011 https://www.ngs.noaa.gov/PUBS_LIB/Floodplain_Pilot_Project_Final.pdf

[26] It has become necessary in some areas to examine both sea level rise and water withdrawal at the same time, since some of what appears to be sea level rise may be the result of land subsidence. John Palatiello, "Subsidence Survey Would Aid in Climate Controversy," *pobonline*, January 14, 2019 https://www.pobonline.com/articles/101556-subsidence-survey-would-aid-in-climate-controversy

[27] Robotic total stations which utilize GNSS provide very accurate vertical measurement, but gravity is needed to tie the data together.

required and or facility life spans shortened. The California High Speed Rail project had major problems in the Central Valley because tracks subsided.[28]

In California, the greatest need for better vertical control is for maintenance of aqueducts that carry water throughout the state. Raising locks and making physical improvements is critical because of subsidence. Moreover, in 2018 flood water was higher than some aqueducts, so water wouldn't flow. More generally, vertical control is needed to assure placement of dams, pipelines and other infrastructure that relies on gravity for water to flow.

USACE uses NGS vertical control to develop levees. Accurate and up-to-date information is required to allow for height of water flow and subsidence. The U.S. Army Corps of engineers rebuilt the New Orleans levee system at a cost of $14 billion after Hurricane Katrina. A proposed project on the Texas-Louisiana border is slated to cost $500 million.

One expert described the forthcoming modernized reference frames and geopotential datum as "a massive boon to infrastructure."

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Crustal motion can be monitored to determine whether bench marks for which there is precise gravity measurement might have to be repaired or replaced or projects that relied on them after they were disrupted have to be corrected

The Congressional Budget Office estimates that "for most types of damage caused by storm surges, heavy precipitation, or high winds from hurricanes or tropical storms, expected annual economic losses total $54 billion." Federal, state and local government spending to address the public sector costs of this damage totaled $147 billion in 2017 dollars.[29] Better measures of heights of evacuation routes and levees can save lives.

USGS uses changes in vertical levels to monitor ground water extraction in aquifers. Accurate orthometric heights are essential for positioning tide gauges and determining the amount of sea level rise to address flooding.[30] Mean ocean dynamic topography (MODT) and mean sea surface topography (MSST) are currently calculated between tide gauges based on models that use data from leveling. With the Gravity Program they will instead be determined at any point based on GPS and a geopotential

[28] Amy, Quinton, "That Sinking Feeling: Valley Land Subsidence Poses Problems for Water, High Speed Rail," Valley Public Radio, November 21, 2013 https://www.kvpr.org/post/sinking-feeling-valley-land-subsidence-poses-problems-water-high-speed-rail

[29] Congressional Budget Office, *Expected Costs of Damage from Hurricane Winds and Storm-Related Flooding*, April 2019 https://www.cbo.gov/publication/55019?utm_source=feedblitz&utm_medium=FeedBlitzEmail&utm_content=812526&utm_campaign=0

[30] See U.S. National Oceanic and Atmospheric Administration, National Ocean Service, *Technical Considerations for Use of Geospatial Data in Sea Level Change Mapping and Assessment*, NOAA Technical Report NOS 2010-01, September 2010 https://www.ngs.noaa.gov/PUBS_LIB/Technical_Use_of_Geospatial_Data_2010_TM_NOS_01.pdf

model. The NGS Gravity Program will support comprehensive coastal and marine spatial planning through an accurate geodetic and tidal reference system. It will lead to better understanding of storm surge for coastal and terrestrial regions through the use of consistent definitions across regions.[31]

Figure 2. U.S. High Tide Flooding and Coastal Sea Levels

Source: NOAA National Ocean Service, Center for Operational Oceanographic Products (CO-OPS), "State of High Tide Flooding (2017 Recap)" https://tidesandcurrents.noaa.gov/HighTideFlooding_AnnualOutlook.html

Combining height, horizontal, ocean, wind and storm surge information allows the determination of how far water will go inland.[32] Better knowledge of topography along with wind information is important for understanding offshore disturbances far out in the continental shelf that lead to storm surges inland. Elevation data is used for assessing flooding from rivers and lakes as well. The sustainability of marine fisheries will be enhanced with better knowledge of the oceanic nutrient transport system.[33]

The societal value of improved height measurement for anticipating and addressing the impacts of storms may be greater in the future if there is an increase in the frequency and severity of extreme weather.

The societal value of improved height measurement for anticipating and addressing the impacts of storms may be greater in the future if there is an increase in the frequency and severity of extreme weather.

While the Gravity Program can improve societal outcomes in many ways, most of the benefits which it has been possible to measure in this study relate to cost savings or avoided costs.

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[31] Mapping with LiDAR, which used for example in the USGS Flood Inundation (FEM) maps and National Map, and by many surveyors and others, must be anchored to orthometric heights.

[32] For example, Sea, Lake and Overland Surges from Hurricanes (SLOSH) models are used in shallow waters.

[33] Dru A, Smith and Daniel R. Roman, "How NOAA's GRAV-D Project Impacts and Contributes to NOAA Science," April 29, 2010 https://www.ngs.noaa.gov/GRAV-D/pubs/GRAV-D_Contribution_to_NOAA_Science.pdf

Opportunities for Accuracy Improvement and Cost Savings

Leveling provides greater accuracy than GPS-derived orthometric heights at short distances – it can be at the mm level for those who need it. Leveling will continue to be done locally for those who need mm accuracy. However, the Gravity Program can still provide cost savings over local leveling at distances below 20 km.

The accuracy of GNSS combined with geoid models is about the same as leveling at the 20-200 km level. However, leveling at those distances can take several weeks in the field and would be far costlier. The greatest cost savings are expected to come in this range.

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NOAA's *Blueprint for 2022, Part 2* notes that "the geoid model based on gravity data and theory disagreed with the NAD83 and NAVD data at the level of a few meters."[34] Accuracy standards which reflect acceptable errors vary greatly among types of applications and with distance.[35] Standards for maps are much coarser than those for surveying. Accuracy standards in practice can result from users or authorities setting standards by accepting what is available. Consequently, the change from expected vertical accuracy from one meter or longer with NAVD 88 to 1-2 cm in many places with the new datums can be expected to result in large improvements in accuracy obtained in practice as use is phased in.[36]

Use of Technologies

Not all applications require the level of accuracy that will be provided by the new GPS-derived heights. For example, the enhanced 911 requirement for identifying the floor of a building at which there is an emergency is 3 meters. A recent European study determined that height requirements for autonomous vehicles are in meters.[37] Some scientific and mining applications require greater accuracy than NGS data

[34] U.S. National Oceanic and Atmospheric Administration, National Geodetic Survey, *Blueprint for 2022, Part 2: Geopotential Coordinates*, NOAA Technical Report NOS NGS 64, November 13, 2017, p.11 https://geodesy.noaa.gov/PUBS_LIB/NOAA_TR_NOS_NGS_0064.pdf

[35] For example, see J. Paul Guyer, *An Introduction to Accuracy Standards for Land Surveys*, Continuing Education and Development, Inc., 2017 https://www.cedengineering.com/userfiles/An%20Introduction%20to%20Accuracy%20Standards%20for%20Land%20Surveys.pdf

[36] Three out of four respondents to the calendar year 2011-2012 question on the Foresee Survey were land surveyors, a large enough group to examine. Their responses were 32% <1 cm, 44% 1-3 cm, and 15% 3-5 cm. Accuracy needs differ among types of users and applications, and they could be more stringent in 2022. There was not enough time to add questions to the Foresee survey and get a large enough number of responses to assess how requirements might have changed since the question was asked.

[37] European GNSS Agency, *Report on Road User Needs and Requirements*, October 18, 2018 https://www.gsc-europa.eu/system/files/galileo_documents/Road-Report-on-User-Needs-and-Requirements-v1.0.pdf

will provide and for which users make measurements on their own. [38] Some applications involve local distances shorter than those at which the Gravity Program has an advantage.

Various technologies are in use that do not require precise orthometric heights. Multi-beam sonar is employed in hydrographic surveys of the depth and contours of the sea floor to inform dredging and removal of obstacles and to maintain safe vessel drafts. Oil drillers use geomagnetic referencing for drill bit positioning based on continuous monitoring of the earth's magnetic field by the U.S. Geological Survey.[39]

Some farms employ sensors on farm equipment to obtain heights for variable rate applications of seed, fertilizer and/or pesticides. A system with millimeter vertical accuracy is available for use in fine grading, milling and paving.[40] These only require local accuracy and not accuracy over the distances that the Gravity Program addresses). NASA's CYGNSS microsatellites use reflected GPS signals to detect wind speed which affects the choppiness of the ocean, in order to detect floods.[41]

However, many technologies provide relative precision but still need an accurate reference point to be usable (e.g. LiDAR and).

Light Detection and Ranging (LiDAR), which uses a laser, scanner and GPS receiver to obtain 3D information about the shape of the earth and its characteristics, requires accurate orthometric heights as a reference and will rely on orthometric heights derived from the NGS Gravity Program. Dru Smith, NGS Modernization Manager, describes LiDAR's operation with aircraft as follows:

> "LiDAR-based products come out of the processing of two instruments. The first is a GPS receiver (or 2 or 3) on board the plane. The processing of GPS on a moving platform is called kinematic GPS and NGS does NOT offer a product which does this. Commercial software will do so. Usually it requires GPS receivers on the ground, and those can be (but aren't always going to be) from the NOAA CORS Network. The second instrument is the LiDAR instrument itself which, combined with the GPS processing will yield up a point cloud in XYZ or in geodetic latitude, longitude and ellipsoid height. In order to get orthometric heights, the processor will need to apply a geoid model. In the future this will be a perfect relationship, by definition. That is, H = h - N will close."[42,43]

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[38] Ground level (surface) gravity measurement by bootstrapping from stations at which NGS has established accurate gravity measurements is not widely done. It is used, for example, by a small number of hydrologists and people in mining who are looking for dense rock. Most of those with a need for very precise gravity measurement collect the data for themselves with gravimeters because they need more precise measurements than can be obtained from NGS or are too far from locations where NGS has established precise gravity.

[39] Institute of Navigation, "A Modern Compass Improves Oil Production," ION Newsletter (Spring 2014), p.15 https://www.ion.org/newsletter/upload/v24n1.pdf

[40] Inside GNSS, "Topcon Technology Roadshow Provides Unique Interactive Opportunities for Attendees," insidegnss.com, October 28, 2018 https://insidegnss.com/topcon-technology-roadshow-provides-unique-interactive-opportunities-for-attendees/

[41] U.S. National Aeronautics and Space Administration, "Flood Detection a Surprising Capability of Microsatellites Mission," sciencedaily.com, July 26, 2018 https://climate.nasa.gov/news/2772/flood-detection-is-a-surprising-capability-of-microsatellites-mission/

[42] H is orthometric height, h is ellipsoid height, and N is geoid height. Their relationship is depicted in Appendix A.

[43] Correspondence with the author, May 20, 2019.

Terrestrial LiDAR is used to monitor volcanoes, earthquakes and mining subsidence, and to measure cliffs, quarries and buildings. It is precise to 2 mm but its accuracy depends on the accuracy of the geopotential datum and it is expensive to deploy.

LiDAR from planes and satellites can have resolutions around 10 cm. Able to cover large areas, it is used to produce digital elevation maps (DEMs) for geographic information systems, make shoreline maps, and assist in emergency response operations and other activities. In bathymetric applications it measures the shape of the underwater terrain.[44] LiDAR also is used from a number of other platforms including ships and UAVs. When UAVs are close to the ground they can get resolutions of around 5 cm.[45,46] They can often reach areas that are difficult or dangerous to access. LiDAR mapping with UAVs is growing rapidly in a wide range of applications. Its use is particularly extensive in agriculture, but still in its infancy.[47] However, whichever platform LiDAR is used on, it can encounter obstructions that tilt its response, so it has to be tied to the geopotential datum, except for some smaller projects. The vertical reference often is required for producing maps. Hence. the accuracy of LiDAR in all of these platforms depends on the accuracy of the geopotential datum.

Interferometric Synthetic Aperture Radar (IfSAR) provides lower resolutions than LiDAR when used above the surface but is cheaper. It is particularly useful in Alaska because of its ability to operate in harsh weather. It too depends on orthometric heights for accurately combining images of parts of a site
A number of other technologies are available which are primarily used for scientific and/or mapping purposes, including maintaining the International Terrestrial Reference Frame.[48] These include Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging, and Doppler Orbitography and Radio Position Integrated by Satellite (DORIS).[49]

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[44] Bathymetry is also done with multi-beam sonar.

[45] For example, Mary Wagner, "Coastal Monitoring Survey Adopts New Tools," *POB*, March 4, 2019 https://www.pobonline.com/articles/101587-coastal-monitoring-survey-adopts-new-tools

[46] Trunick recently reported resolutions for three programs:

- The National Agriculture Imagery Program which provides statewide coverage of agricultural states during the Summer peak agricultural season is moving from 1 meter to 60 cm resolution.
- The Geospatial Intelligence Center's Blue Sky Program covers the continental U.S. under ideal weather conditions with 20 cm resolution.
- The Geospatial Intelligence Center is launching a Metro Mapping Program for the top 150 metropolitan areas at 7.5. cm.

Perry Trunick, "Aerial Mapping Opportunities Abound," *POB*, March 18, 2019 https://www.pobonline.com/articles/101591-aerial-mapping-opportunities-abound?oly_enc_id=6344G7874812H1K

[47] Renee Knight, "Precision Agriculture: The Trends and Technologies Changing the industry," *insideunmannedsystems.com*, April 9, 2019 http://insideunmannedsystems.com/precision-agriculture-the-trends-and-technologies-changing-the-industry/

[48] GPS World Staff, "NASA Helps Maintain International Terrestrial Reference Frame," gpsworld.com, February 29, 2016 https://www.gpsworld.com/nasa-helps-maintain-international-terrestrial-reference-frame-with-gnss/

[49] California collects data that is more granular than the NGS reference frame to monitor local effects of earthquakes and floods, but ties the data to NGS, without which it would not be as reliable.

Types and Numbers of Users of Height Information

Occupation and Industry

Information on numbers and characteristics of persons in occupations and economic sectors that make use of NGS services is obtained from the U.S. Bureau of Labor Statistics (BLS). Many in occupations directly using NGS data provide services to others who rely on their services (such as a state road department contracting with surveyors for GIS services). Additional information comes from studies of geoservices industries which are discussed in the sections on market size and benefits and employment data from the U.S. National Science Foundation (NSF) which is in Appendix F.[50]

BLS data on employment in selected occupations is shown in Table 1. The table includes both occupations that make extensive use of NGS services and some that may not have a majority of practitioners directly using the services.

Civil engineers are by far the largest category. An estimated 5,884 persons who were dual engineers and surveyors took state licensing exams in 2015 vs. 55,475 surveyors, putting dual engineers and surveyors at 9.6% of the total of the two categories. In 2016 the number of dual engineers and surveyors taking the exam was 5,313 and the number of surveyors 51,091, with dual accreditation accounting for 9.4% of the total.[51] Data is not available on the number of unaccredited engineers doing surveying, how frequently they do it or how that has changed over time.

Table 1. Employment by Occupation, 2007-2017

Occupation	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Surveyors	56,670	55,780	50,360	43,950	42,020	40,190	41,360	41,970	43,140	43,340	43,430
Surveying and mapping technicians	72,410	71,920	62,940	53,870	48,590	47,000	47,950	50,750	53,620	53,920	51,890
Cartographers and photogrammetrists	11,460	11,690	11,750	11,670	11,240	11,490	11,290	11,610	11,970	12,100	11,440
Geoscientists, except hydrologists and geographers	31,390	31,260	31,860	30,830	32,490	35,180	34,690	34,000	31,800	30,420	28,520
Hydrologists	7,670	7,590	7,150	6,910	6,960	6,880	6,540	6,580	6,580	6,300	6,350
Civil engineers	247,370	261,360	259,320	249,120	254,130	258,100	262,170	263,460	275,210	287,800	298,910
Geographers	1,010	1,120	1,170	1,300	1,430	1,510	1,480	1,260	1,280	1,370	1,400
Foresters	10,510	10,160	10,230	9,470	9,000	9,470	9,220	9,140	8,590	8,420	8,300
Forest and conservation technicians	26,900	30,850	31,440	32,290	30,620	31,720	29,740	30,310	29,810	30,090	30,570
Geological and petroleum technicians	13,060	14,570	14,460	13,560	14,680	15,360	15,190	16,020	16,820	15,100	14,820
Agricultural Engineers	2,480	2,640	2,620	2,520	2,650	2,470	2,590	2,450	2,330	1,980	1,770
Mining and geological engineers, including mining safety engineers	7,150	6,900	6,310	6,270	6,630	7,640	7,990	8,200	8,000	6,940	6,150

Source: https://www.bls.gov/oes/tables.htm

[50] Detailed industry and product data which includes employment and payroll from the U.S. Department of Commerce *2017 Economic Census* is scheduled to be released over a period of years beginning in September 2019. The previous economic census contained data for 2012. See https://www.census.gov/programs-surveys/economic-census.html

[51] ARCBridge Consulting and Training, *Scoping the Value of the NGS Regional Geodetic Advisor Program*, Final Report, revised June 1, 2018, p.24 https://www.ngs.noaa.gov/PUBS_LIB/reg-geodetic-advisor-prog-socio-economic-scoping-study-6-1-18.pdf

The concentration of geoscience occupations varies greatly by industry as analyzed in the ARCBridge Regional Geodetic Advisors socio-economic benefits report.[52] The data was based on the BLS tables of occupation by industry for 2016. Some highlights are:

- 37.5% of surveyors are in the engineering services industry and 2.5% in self-employment vs. 10.9% in government
- 27.1 of surveying and mapping technicians are in the engineering services industry and 10.2% in self-employment vs. 16.5% in government.
- Hydrologists are particularly prevalent in federal, state and local government.
- Cartographers and photogrammetrists are concentrated in local government.
- Geographers are disproportionately in the federal government.
- Geoscientists except hydrologists and geographers are the most numerous in engineering services, management, scientific and technical consulting services sectors, and in oil and gas extraction.
- Half of civil engineers are in the engineering services industry, while nearly one-fourth are in state and local government.

In recent years, growth has been evident among civil engineers, geographers, and geological and petroleum technicians. Table 2 shows BLS projections by occupation through 2026. The most rapid increases are projected for cartographers and photogrammetrists and for geoscientists, except hydrologists and geographers.

[52] *Ibid*.

Table 2. BLS Employment Growth Projections, 2016-2026			
	2016 (thousands)	**2016-2026 change** (thousands)	**percent change**
Surveyors	44.8	5.0	11.2
Surveying and mapping technicians	60.2	6.4	10.6
Cartographers and Photogrammetrists	12.6	2.4	19.4
Geoscientists, except hydrologists and geographers	32.0	4.5	13.9
Hydrologists	6.7	0.7	9.9
Civil engineers	33.2	1.3	3.8
Geographers	1.5	0.1	6.2
Forest and conservation technicians	33.2	1.3	3.8
Geological and petroleum technicians	15.0	2.5	16.4
Mining and geological engineers, including mining safety engineers	7.3	0.5	7.2
Source: https://www.bls.gov/oes/tables.htm			

Total Geospatial Employment and Spending Estimated Based on BLS Occupation Data

The sum of employment in 2017 is 155,030 for surveyors, survey and mapping technicians, cartographers and photogrammetrists, geoscientists, except hydrologists and geographers, hydrologists, geographers, and an assumed 12,000 for civil engineers doing surveying.[53] Considering possible geospatial activities in other occupations listed and assuming no change in total geospatial employment between 2017 and 2018, a rough estimate is employment in geospatial activities in 2018 is 170,000-190,000.

This estimate based on occupation data compares with an illustrative estimate for the U.S. of 204,786 in 2013 based on the size of the Canadian private geospatial sector found in the Canadian Geomatic and Environmental Scan and Value Study[54] and the relative GDP of the U.S. and Canada. The estimate is described art the end of this chapter.

[53] Assuming the same proportion of full and part time as in the sum of the other occupations.

[54] Hickling Arthurs Low, *et. al.*, *Value Study Findings Report*, prepared for Natural Resources Canada, 2016 https://geoscan.nrcan.gc.ca/starweb/geoscan/servlet.starweb?path=geoscan/fulle.web&search1=R=297711

Direct spending on geospatial activities is estimated by applying a range of values for spending per employee to the employment numbers. For this purpose, $130,000-$160,000 per employee is used. Spending per employee roughly allows for average salaries, benefits and overheads, the cost of support staff, and profits of survey and engineering firms, and allows for some employees working part time.

Multiplying 170,000-190,000 by $130,000-$160,000 yields an estimate of spending of $22.1-$30.4 billion in 2018. This does not include multiplier effects on spending in the rest of the economy.

U.S. spending estimate was compared with an estimate based relative size in data from the Canadian Geomatic and Environmental scan and Value study which included only the Canadian private sector.[55] That estimate, which is described later, was of U.S. spending of $25.6 billion in 2018, which falls within the range of the U.S. estimate of $22.1-$30.4 billion.

Survey Data on NGS Clients

Foresee Survey

The Foresee survey is administered to visitors to NGS Web sites that are willing to participate. Half of respondents to the Foresee survey identified themselves as land surveyors (Table 3). Twelve percent of

Table 3. Which Term Best Describes Your Role?

Role	2016 (N=672)	2017 (N=1012)	2018 (N=1091)
Land Surveyor	56%	49%	50%
Engineer	12%	12%	13%
Cartographer/GIS Mapping User	7%	9%	8%
Researcher	7%	8%	7%
General Public	5%	6%	7%
Geodesist	4%	6%	5%
Other	4%	4%	4%
Student	3%	3%	3%
Educator	2%	2%	2%
Geocacher	1%	1%	1%
News Media	0%	0%	0%

Source: Responses to Foresee Survey, Jan. 2016-Dec. 2018.

[55] Hickling Arthurs Low, et. al., *Canadian Geomatics Environmental Scan and Value Study, Summary Report*, Prepared for Natural Resources Canada, 2016 http://ftp2.cits.rncan.gc.ca/pub/geott/ess_pubs/296/296426/cgdi_ip_41e.pdf

those reporting in 2017 were engineers, which is double the percent of engineers in the total of engineers and surveyors taking surveyor licensing exams. Nine percent of respondents were cartographers or GIS mapping users, 8% were researchers and 5% were geodesists.

Forty four percent of those reporting in 2017 primarily used NGS data for geodetic quality control or for deeds, plats and boundaries (Table 4). Nine percent used NGS data for FEMA flood certification. Nine percent used the data for transportation and 8% for construction.

Use of NGS data varies greatly among occupations. The most prevalent use among land surveyors was geodetic quality control at 32%, with deeds, plats or boundaries next at 26%. Among engineers, 18% reported using NGS data for construction and 18% for geodetic quality control. Not surprisingly, 68% of geodesists used it for geodetic quality control.

Table 4. What Do You Primarily Use NGS Data For?

Use of NGS Data	**2016** (N=672)	**2017** (N=1003)
Geodetic quality control	28%	27%
Deeds, plats, or boundaries	17%	17%
FEMA flood certification	10%	9%
Transportation (roads, waterways, bridges, or tunnels)	9%	9%
Construction	7%	8%
Urban planning	3%	2%
Agriculture and/or crop management	1%	1%
Other	14%	15%
Not applicable – I am visiting this site for other reasons	11%	11%

Source: Responses to Foresee Survey, Jan. 2016-Dec. 2017.

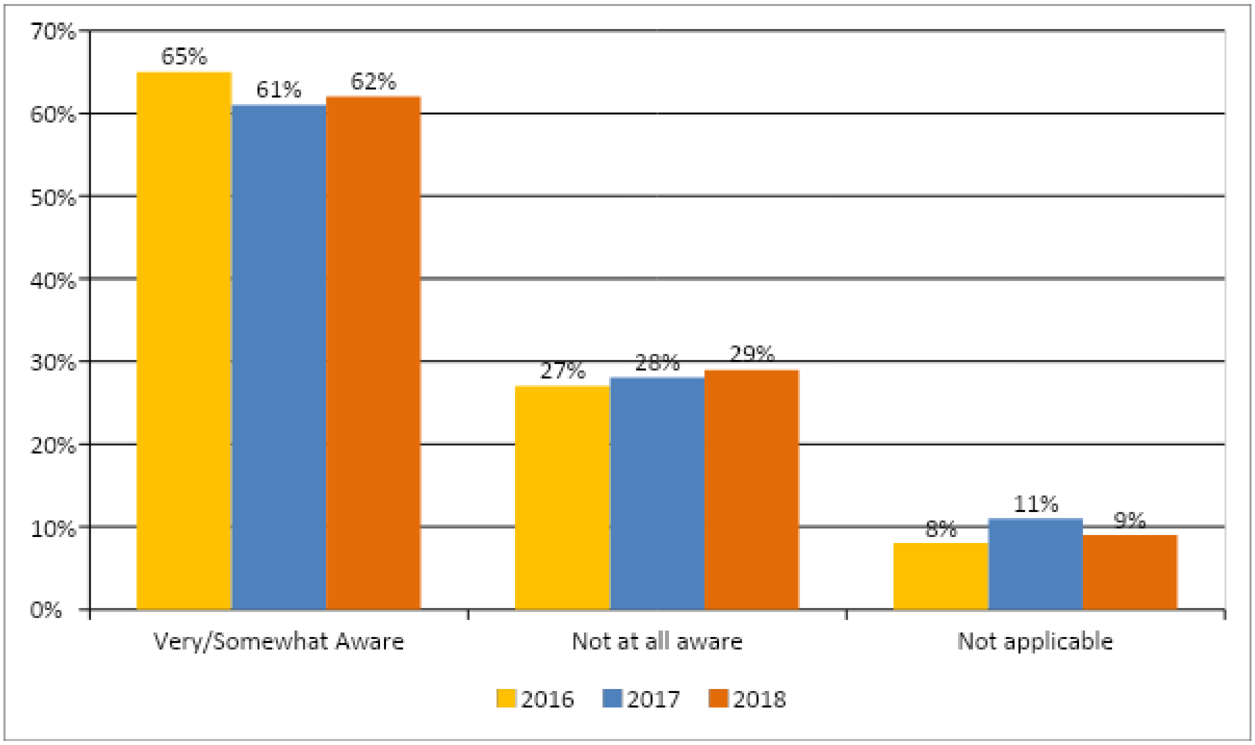
Eighty percent of reporting visitors to the NGS Web site in 2018 were primarily looking for CORS or OPUS, data sheets, toolkit software or guidelines or specifications (Table 5). This suggests that many users of the Web site are strong candidates to make early use of products and services derived from the NGS Gravity Program. However, not all visitors are prepared, and the current use data does not shed light on the broader population of potential users of the data and services who may have different needs or understanding.

Table 5. What Were You Primarily looking for on This Visit to the Website?

Looking for	2016 (N=672)	2017 (N=1012)	2018 (N=1091)
CORS/OPUS	47%	43%	41%
Datasheets	21%	17%	20%
Toolkit software	11%	12%	11%
Guidelines or specifications	7%	9%	8%
Imagery/LiDAR	2%	8%	8%
News	2%	2%	2%
Other	10%	10%	10%
Source: Responses to Foresee Survey, Jan. 2016-Dev. 2018.			

Despite extensive NGS publicity, over 2016-2018 only 62% of visitors to the NGS Web site reporting in the Foresee survey indicated that they were aware or somewhat aware that NGS will replace NAVD 88 with new geometric and geopotential datum (Figure 3). 28% were not at all aware, while one in ten stated that it was not applicable or they were visiting the site for other reasons. There is no indication that awareness increased during the period.

Figure 3. Awareness that NGS Will Replace NAVD 88 with a New Datum



Sample Size: N=672 in 2016, N=1,012 in 2017 and N=1,091 in 2018.

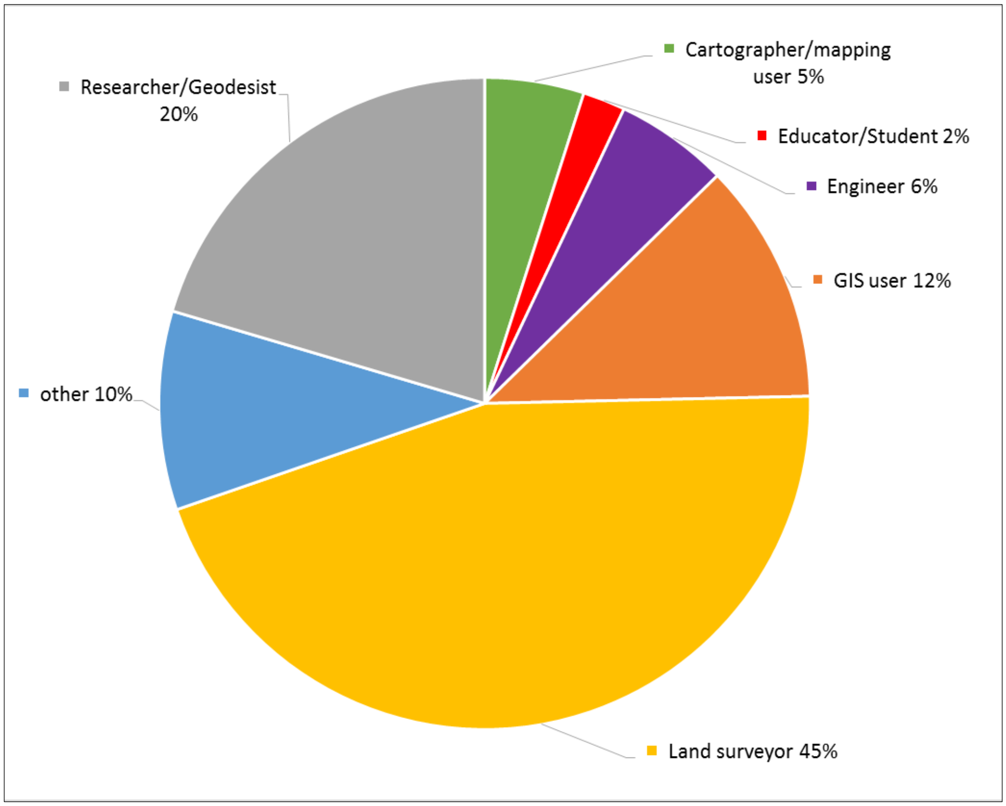
Surveys of NGS 2017 Geospatial Summit Attendees

Data from the 2017 Geospatial Summit surveys of participants on April 24 and April 25, taken on each of the days of the conference, is also of interest. Ninety-seven of 436 participants in the 2017 Geospatial Summit were NGS employees. Another 59 worked in NOAA other than NGS. The large number of NGS employees would appear to account for the higher proportion of surveyors in the Geospatial Conference surveys than in the Foresee survey (53% vs. 34%). The concentration of NGS and other NOAA employees would also appear to account for 20% of those responding to the Geospatial Summit survey classifying themselves as "researchers or geodesists."

To determine responses of NGS clients, data for those self-reporting as NGS employees and those who did not answer the question about whether they were NGS employees were excluded from both the April 24 and April 25 survey responses.

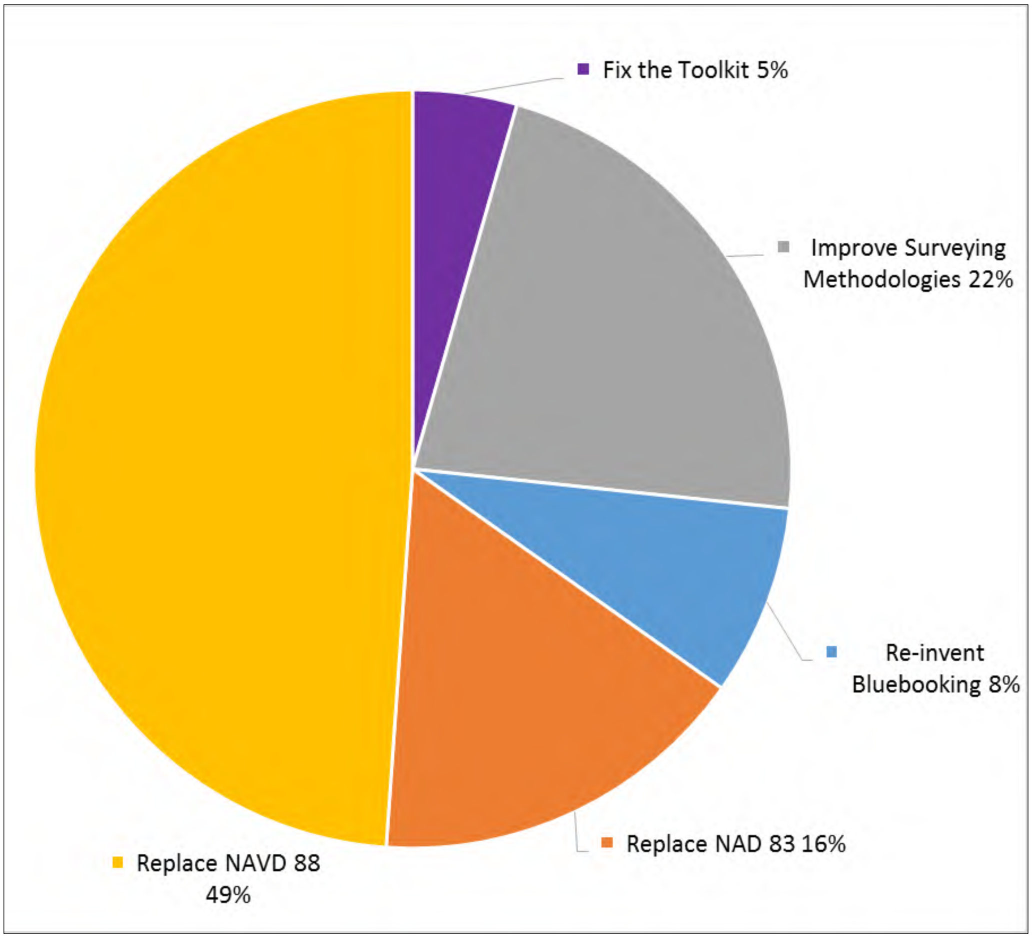
Forty-five percent of the included respondents in the April 24 survey reported being land surveyors and 20% indicated they were researchers or geodesists. Twelve percent were GIS users (Figure 4). In the April 25 survey, 53% of those we included reported being land surveyors, 20% said they were researchers of geodesists, and 8% were GIS users.

Figure 4. Which Term Best Describes Your Role? (Apr 24; n=142)



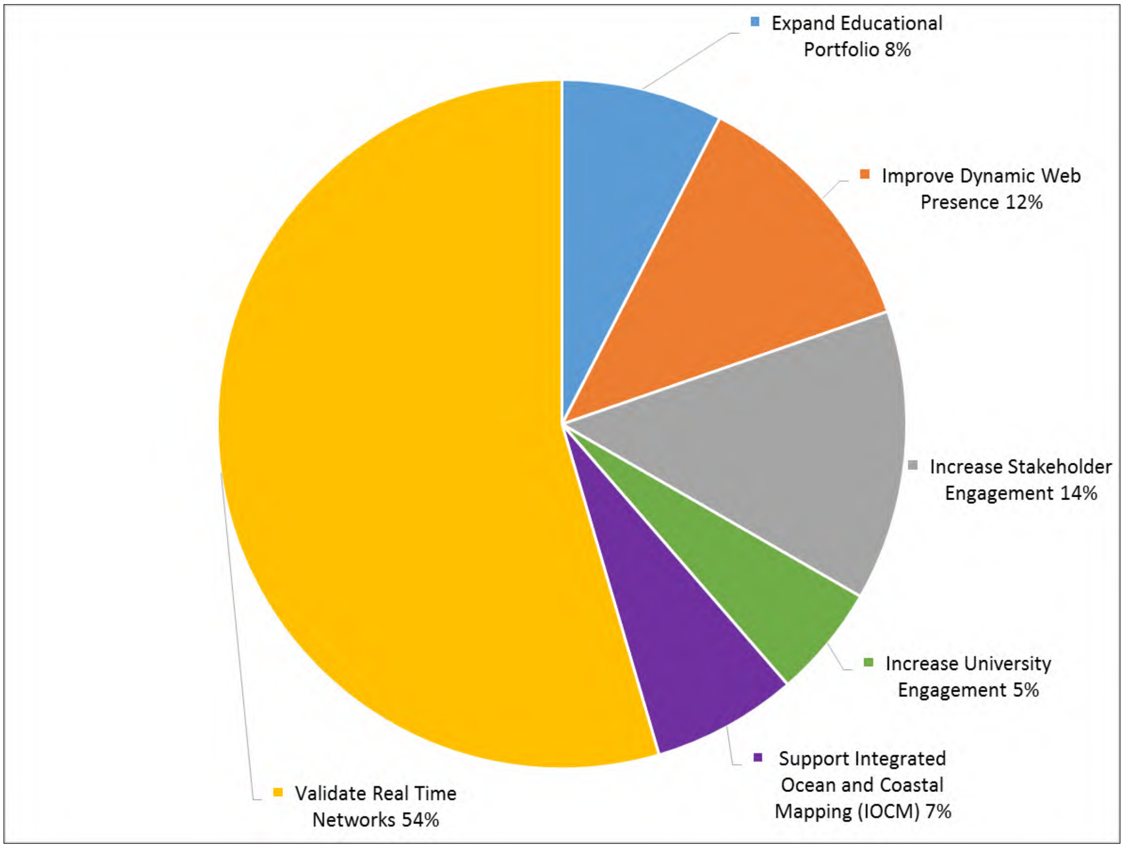
When asked what is most critical to modernize the NSRS on April 24, 49% said “replace NAVD 88, while 22% said “improve survey methodologies” and 16% said “replace NAD 83” (Figure 5).

Figure 5. What Is Most Critical to Modernize the NSRS? (n=135)



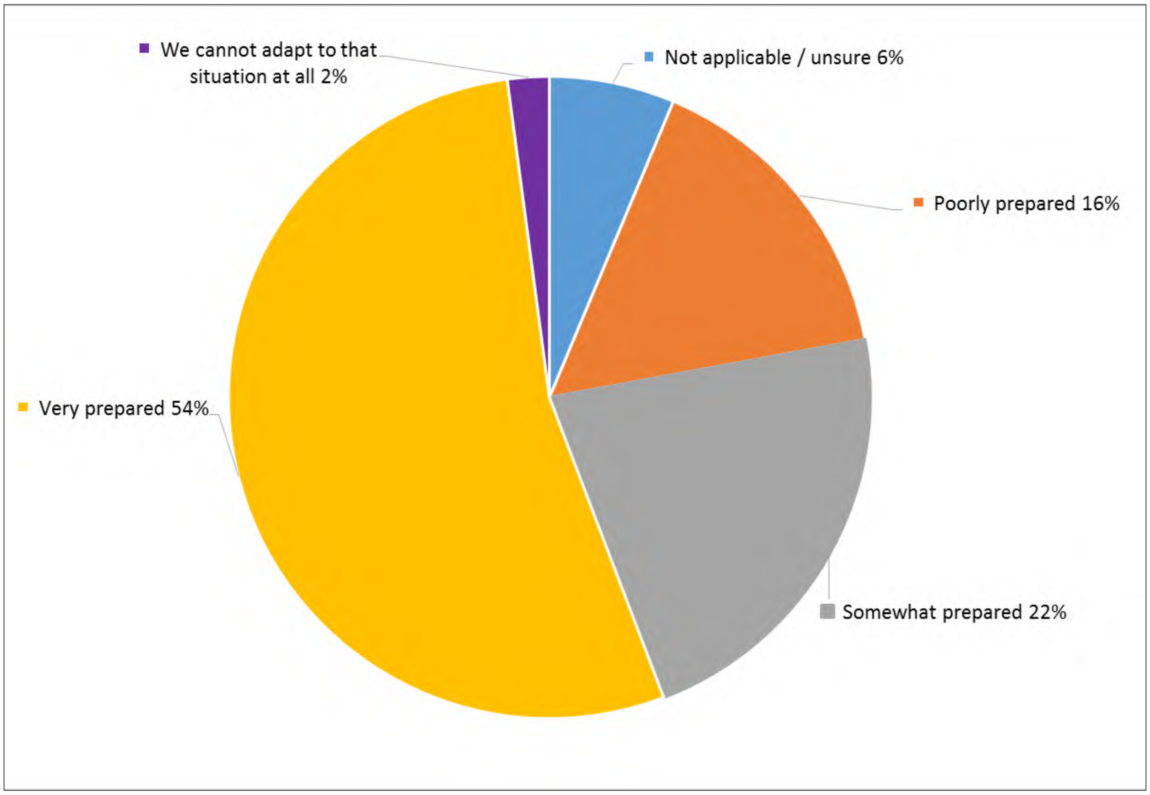
The April 24 questions are useful in understanding how long it may take for use of the new datum to be phased in. The first shows desire for support while the second shows readiness to access the new system. When asked on what is most critical to support NGS customers, 54% said “validate real time networks” and 12% said “improve dynamic Web presence,” while 27% chose “increase stakeholder engagement,” “increase university engagement,” or “expand educational portfolio” (Figure 6).

Figure 6. What Is Most Critical to Support NGS Customers? (n=132)



When asked how prepared their agency was "to use Continuously Operating Reference Stations (CORSs) as the primary access to the National Spatial Reference System," 54% replied "very prepared," 22% answered "somewhat prepared," and 24% said they were "poorly prepared," "not applicable or unsure," or "we cannot adapt to that situation at all" (Figure 7).

Figure 7. How Prepared Is Your Agency to Use Continuously Operating Reference Stations (CORS) as the Primary Access to the National Spatial Reference System (NSRS)? (n=95)



Surveys of NGS 2019 Geospatial Summit Attendees

Advance information is available from surveys of participants in the May 6-7, 2019 Geospatial Summit which will be published shortly in a Summit report. The discussion here is on questions for which responses were reported separately for attendees who were not NGS employees. Responses of attendees by Webinar as well as in person are included.

Keep in mind that those participating in NGS Geospatial Summits may be more knowledgeable that the overall population of potential users or unrepresentative in other ways, and that different combinations of people answered each question. One way this is evident is in difference in responses between the two days. Also, questions about the NSRS refer to more than the Gravity Program. For these reasons, comparisons are not made with data from the 2017 Summit.

Thirty eight percent of Day 1 respondents who were not NGS employees said they felt excited about NSRS modernization while 44% were both excited and concerned and about 18% were either concerned or did not feel they had enough information. Among Day 2 respondents, 48% were excited and 42% were both concerned and excited.

Twenty four percent of non-NGS Day 1 respondents indicated that they were very prepared for NSRS modernization while 44% were a little prepared, 22% were not at all prepared and about 10% did not feel they had enough information. Among Day 2 respondents, 41% were very prepared, 37% were a little prepared and about 22% were not at all prepared or didn't feel they had enough information.

Use of NGS Services

NGS Web page user statistics that count the number of times NGS software runs a calculation show marked shifts. Over the years, growth has been strong in use of OPUS, OPUS Rapid Static, CORS and User Friendly CORS (Table 6). Regular OPUS use increased sharply in FY 2018. Use of datasheet and shapefiles has declined, while the use of tool kit applications has fluctuated.

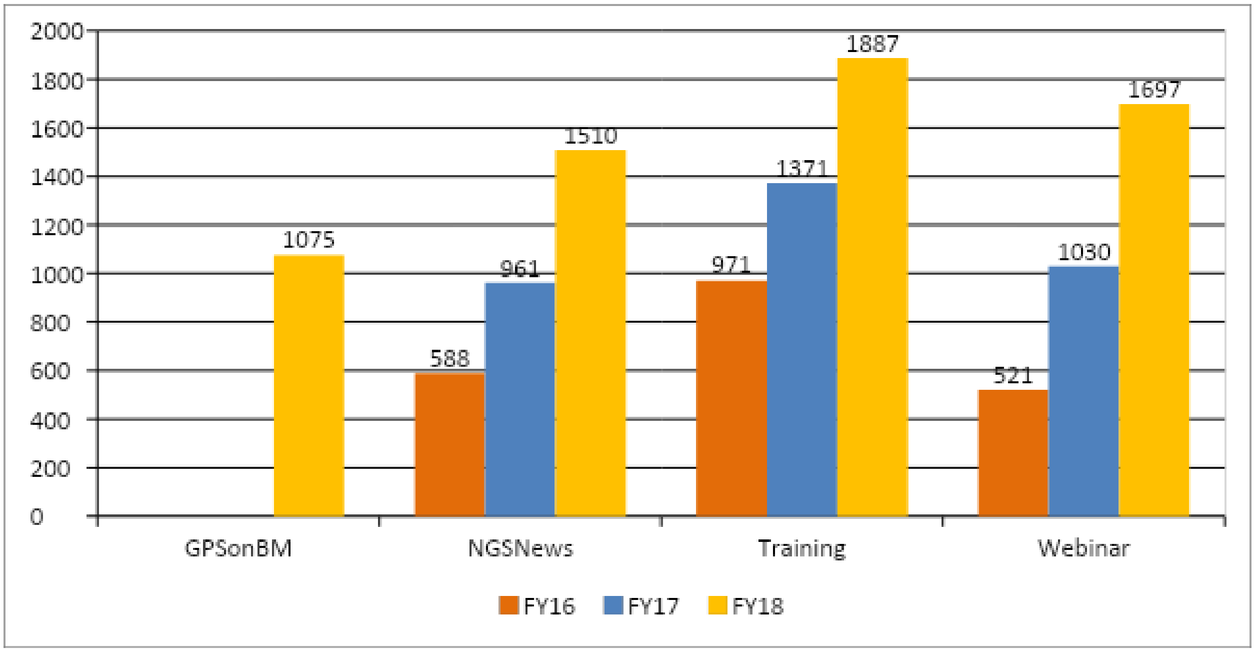
Table 6. NGS Web Page User Statistics

	FY2007	FY2008	FY2009	FY2010	FY2011	FY2012	FY2013	FY2014	FY2015	FY2016	FY2017	FY2018
OPUS												
Regular	201,550	182,108	173,461	172,430	206,940	286,599	232,591	258,696	299,390	314,073	381,822	532,145
RS	31,770	72,190	79,284	100,921	136,168	136,450	129,218	134,339	141,988	129,234	154,958	118,519
UFCORS	950,827	1,042,733	977,390	1,070,995	1,204,331	1,212,604	1,263,519	1,063,226	1,150,056	1,140,508	1,303,584	1,070,913
CORS FTP	5,269,563	9,391,009	9,457,160	14,112,693	19,622,084	44,774,666	41,276,983	31,576,444	35,999,596	64,706,032	59,262,274	50,966,203
Datasheets												
Regular	3,802,758	6,022,082	4,025,759	3,603,791	3,731,545	3,111,082	3,081,928	2,453,275	2,620,293	2,370,295	2,060,225	2,686,504
Archived Counties	11,832	17,291	3,514									
Shapefile	2,425,978	3,954,488	2,687,973	2,117,042	2,400,543	2,438,120	2,248,748	1,545,475	1,584,848	984,963	840,880	817,359
Tool Kit Applications												
NADCON	370,738	550,487	1,088,588	1,723,079	687,351	656,020	588,538	535,428	670,507	347,367	169,749	180,458
VERTCON	45,326	64,721	71,253	102,439	146,643	148,326	237,158	181,311	218,656	275,865	672,051	865,658
Inv_Fwd	15,230	17,380	19,780	18,436	25,041	26,256	38,888	17,526	21,309	49,070	10,282	12,471
HTDP	24,024	106,249	80,038	70,695	34,806	133,904	435,968	513,133	666,824	2,526,657	306,345	39,169
Geoid	1,438,641	2,169,313	976,627	5,264,095	3,206,074	2,413,819	1,339,286	939,846	4,672,299	1,336,501	2,431,148	2,277,049
SPCS	114,650	137,719	205,419	176,368	168,463	198,308	197,238	167,801	148,737	134,665	119,359	101,208

1,599 visits were made to the NGS height modernization landing page in 2017 while 9,016 visits were made to all the height modernization pages. While return visits by the same individual are included, the data indicate that the great majority of these visitors were returning after becoming familiar enough with the site to go more directly to the pages they were interested in.

NGS offers subscriptions to four newsletters, including GPS on Bench Marks which was first available for a full year in FY2016. The other three: NGS News, Training, and Webinar, have shown very rapid growth (Figure 8). The numbers are small compared to the numbers of users of NGS services, but they tend to include those with the greatest skill needs. There is not a lot of information about what organizations subscribers belong to and it is not possible to tell how many of the same individuals subscribe to multiple newsletters.

Figure 8. Subscriptions to NGS Newsletters, FY2016-FY2018



Direct information is available on training. There were 4,018 visits to the site of the Corbin Training Center calendar of classes for OPUS training in 2017. Training occurs both through classes and Webinars (Table 7). Once trained, people can continue to use the OPUS service on their own so, in spite of increased use (see below), OPUS Projects training has declined in recent years. However, there may be a large increase in use of training closer to when the new datums become available and thereafter because of a need for existing users to learn the upgraded system and demand from new users.

Table 7. OPUS Projects Training, FY2014-FY2018

	In-Person		Webinar	
Fiscal Year	Number of Sessions	Number Trained	Number of Sessions	Number Trained
2014	71*	1160*	n.a.	n.a.
2015	28	566	3	59
2016	29**	436**	5	157
2017	19	266	3	119
2018	15	199	4	120

*Includes one session reported as "virtual."
**Includes an on-site session for the U.S. Bureau of Land Management.

Information also is provided to users through the OPUS User Forum pages. There were 334 visits to the OPUS Projects Manager Training Videos pages for further instruction in calendar year 2017.

OPUS static was used for 314,073 cases in FY2016 and OPUS static with solution shared was used for 2,381 cases. OPUS rapid static was used for 129,234 cases. Use of OPUS static has continued to rise. 2,249 OPUS Projects with 6,836 unique marks were created in 2016 by 618 unique users. Demand for OPUS will increase with deployment of the NGS Gravity Program and new datums.

Demand for OPUS will increase with deployment of the NGS Gravity Program and new datums.

The CORS landing page recorded 72,219 visits in 2017, while all CORS pages had 171,275 visits. This compares with 70 million uses of the CORS system at NGS in that year, with the difference reflecting automated use of the system. CORS will become the primary source of access to the National Spatial Reference System when to 2022 changes take place.

Visits to all conference and Webinar pages totaled about 6,000 in 2017 – including visits by the same person multiple times to a site and/or to multiple sites.

Further Indications of Market Size and Importance of Potential Beneficiaries

A range of measures of sectors or activities that might benefit are considered here, including the size of the ocean economy, the extent of water resource activities, ship navigation, and the human cost of flooding and storms.

The Ocean Economy

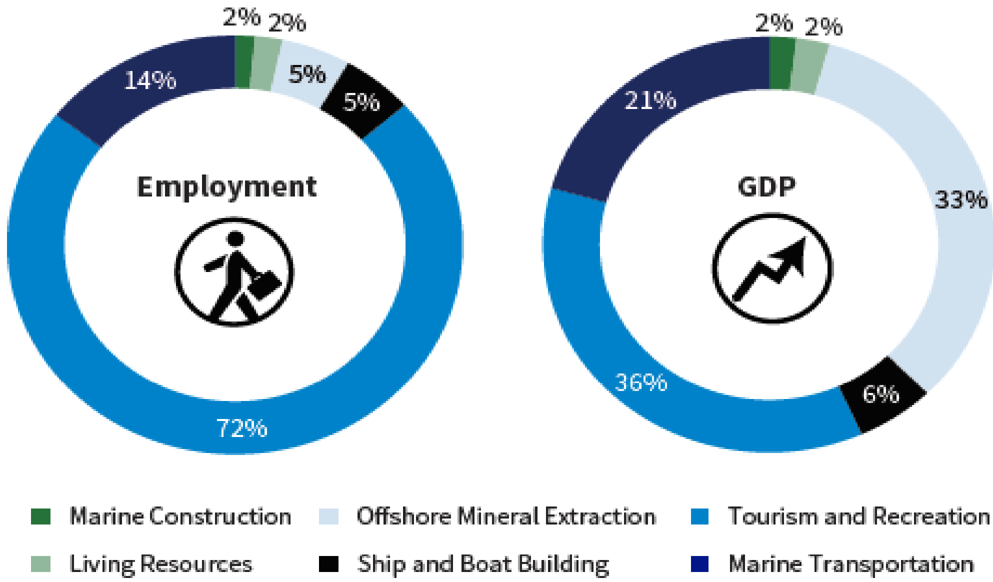
The 2014 economy of the 337 shoreline adjacent counties includes:[56]

- 18.1% of U.S. land area
- 119.3 million people (37.4% of U.S.)
- 51.2 million jobs (37.5% of U.S.)
- GDP of $6.8 trillion (43.2% of U.S.)

The U.S. Ocean and Great Lakes Economy accounted for 3.2 million jobs and GDP of $320 billion in 2005.[57] The largest industry in the ocean and Great Lakes economy in terms of employment is tourism and recreation, with marine transportation the next largest (Figure 9). The largest in GDP is offshore minerals, which is primarily oil and gas, with tourism and recreation the next largest.

[56] National Ocean Economic Project, *State of the U.S. Ocean and Coastal Economies: 2016 Update*, Table 1 http://www.oceaneconomics.org/Download/ and Hickling Arthurs Low, *et. al.*, *Value Study Findings Report*, prepared for Natural Resources Canada, 2016, Table 10 https://geoscan.nrcan.gc.ca/starweb/geoscan/servlet.starweb?path=geoscan/fulle.web&search1=R=297711
[57] U.S. National Oceanic and Atmospheric Administration, Office for Coastal Management, *NOAA Report on the U.S. Ocean and Great Lakes Economy*, 2017, p.3 https://coast.noaa.gov/data/digitalcoast/pdf/econ-report.pdf

Figure 9. Sector Shares of U.S. Ocean and Great Lakes Economy, 2015



Water Transportation

Water transportation plays a vital role in the economy and will depend heavily on orthometric heights derived from the Gravity Program.

- The gross value of output the U.S. water transportation industry was $59 billion in 2013[58]
- Vessels made 68,036 calls at U.S. ports in 2011[59]
- Water transportation moves nearly 70 percent of all U.S. international merchandise trade, including 72 percent of U.S. exports by tonnage[60]
- U.S. Waterborne freight transport was 2.3 billion short tons ion 2016 (Table 9).
- The U.S. inland waterway system extends 25,000 miles and touches 39 states and DC. It includes 192 locks, 68 of which are located at power dams[61]

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[58] U.S. Department of Transportation, Bureau of Transportation Statistics, *National Transportation Statistics*, updated July 2015 https://www.bts.gov/bts-publications/national-transportation-statistics/national-transportation-statistics-previous

[59] *Ibid*.

[60] U.S. Department of Transportation, Bureau of Transportation Statistics https://www.bts.gov/content/us-waterborne-freight

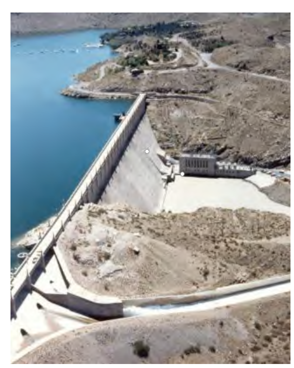
[61] Marisol Bonnet, *et. al*., *The Economic Benefits of Multipurpose Reservoirs in the United States*, Oak Ridge National Laboratory, ORNL/TM-2015/550, September 2015, p.28 https://hydrowise.ornl.gov/sites/default/files/2017-06/The_Economic_Benefits_of_Multipurpose_Reservoirs_in_the_United.pdf

Table 9. U.S. Waterborne Freight, 2016
(millions of short tons)

Foreign total	**1,415.5**
Imports	755.6
Exports	659.8
Domestic total	**876.6**
Inland	548.1
Coastal	168.7
Great Lakes	78.2
Intraport	80.1
Intraterritory	1.5
Total	**2,292.0**

Source: U.S. Department of Transportation, Bureau of Transportation Statistics https://www.bts.gov/content/us-waterborne-freight

Water and Power



Water and power supplies are essential to businesses, governments and households.

- Approximately 62 billion gallons of water per day are used for public, municipal, and industrial uses (excluding mining and livestock)[62]
- The EPA reports that there are over 151,000 public water systems in the United States[63]

[62] Marisol Bonnet, *et. al.*, *The Economic Benefits of Multipurpose Reservoirs in the United States*, Oak Ridge National Laboratory, ORNL/TM-2015/550, September 2015, p.27 https://hydrowise.ornl.gov/sites/default/files/2017-06/The_Economic_Benefits_of_Multipurpose_Reservoirs_in_the_United.pdf

[63] U.S. Environmental Protection Agency, "Information about Public Water Systems," https://www.epa.gov/dwreginfo/information-about-public-water-systems

- Approximately 2,540 dams on rivers produce hydroelectric power[64]

To measure water flow, water data is collected at 27,000 sites around the country with 7 million observations per day. 20,000 sensors measure stream flow. 3092 USGS Federal Priority Streamgages were active on February 12, 2015. This distributed network of computers is called the National Water Information System (NWIS).[65]

The National Weather Service hydrologic modeling, which is done for approximately 4,000 locations across the continental U.S,. is supplemented by its new National Water Model which simulates observed and forecast streamflow across CONU.S..[66] NWS provides storm surge notifications through the National Hurricane Center and local forecast offices.

Public capital spending on water resources and water utilities was nearly $40 billion in 2017. Spending on operations was over $100 billion (Table 10).

Table 10. Public Water Capital and Operations Spending in FY2017
(billions of dollars)

Sector	Capital Spending	Operation and Maintenance
Water transportation	3.7	6.5
Water resources	8.0	20.7
Water utilities	31.4	81.6
Total	**43.1**	**108.8**

Source: Congressional Budget Office, *Public Spending on Transportation and Water Infrastructure, 1956-2017*, October 2018, supplementary tables https://www.cbo.gov/publication/54539

The scale of local government activities is illustrated by the number of single function special purpose local government districts which in 2012 included:[67]

- 3,248 for flood control
- 2,565 for soil and water conservation

[64] American Rivers, "Frequently Asked Questions about Removing Dams https://www.americanrivers.org/conservation-resources/river-restoration/removing-dams-faqs/
[65] https://waterdata.usgs.gov/nwis/nwis
[66] https://water.noaa.gov/about/nwm
[67] U.S. Census Bureau, *2012 Census of Governments*, table on government units by state, 1942-2012 http://facfinder.census.gov/

- 1,522 for other natural resources
- 1,909 for sewerage
- 3,522 for water supply

The Human and Societal Cost of Flooding and Storms

Nearly 90% of emergencies declared by FEMA are weather-related.[68]

There are many indications of the human and societal cost of flooding and storms. Among them are:

- The 30-year period 1988-2017 experienced an average of 86 fatalities per year from floods, according to NOAA hazstats.[69]
  - In 2017, flash floods killed 103 people, injured 8, and caused $59 billion in property and crop damage
  - In 2017, tropical storms and hurricanes killed 43 people, injured 62, and caused $23 billion in property and crop damage
  - Many more were killed by winter storms, river floods and rip currents
- About 240 million calls are made to 911 each year[70]
- More than 1.8 million people are in occupations involving emergency management[71]

Broad Market Studies

This discussion is based on publicly available reports with estimates of overall U.S. market size or Canadian data that can inform the U.S. geospatial industry market size. It does not include proprietary market research studies or reports with only global data.

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[68] American Meteorological Society, "Weather Analysis and Forecasting," information statement adopted March 25, 2015 http://www.ametsoc.org/POLICY/2015_weather_analysis_and_forecasting_information_statement_ams.html

[69] U.S. National Oceanic and Atmospheric Administration, "Natural Hazard Statistics" https://www.nws.noaa.gov/os/hazstats.shtml

[70] NENA, The 911 Association, "9-1-1 Statistics," https://www.nena.org/page/911Statistics

[71] Emergency management and EMT are occupation data from U.S. Bureau of Labor Statistics, "Occupational Statistics from the Current Population Survey," http://www.bls.gov/cps/cpsaat11.htm Police and fire are industry data are from Robert Willhide, *Annual Survey of Public Employment & Payroll Summary Report: 2013*, U.S. Census Bureau, G13-ASOEP, December 19, 2014 http://www2.census.gov/govs/apes/2013_summary_report.pdf

BCG Study of Geospatial Services in the U.S.

The Boston Consulting Group (BCG) conducted a study of the U.S. for Google which made information publicly available only through a three page report issued in June 2012 and a set of nine slides released in December 2012.[72] With limited information on sources and methods, it is difficult to evaluate their validity. the study showed a GREAT propensity for exaggeration by using a multiplier of 15-20 times to arrive at U.S. revenues driven by geospatial services. This compares with a multiplier of 9 in the Canadian Geomatics Environmental Scan and Value Study.[73]

BCG defined geospatial services as those that let decisions be made based on geographic data. The geospatial services industry was defined as: "Groups of companies and organizations providing the tools and technologies for end users to benefit from location-based information."

Findings of the study included:

- The geospatial services industry generated annual revenues of almost $75 billion in 2011 and provided 500,000 high wage jobs.
- Three primary sectors of the industry have the following 2011 revenues:
  - Geo-expert industries $2.6 billion.
  - Geo-applications and devices $54 billion.
  - Location-based geo-data $17 billion (which includes imaging satellite manufacturing and launch, imaging programming and platform providers).[74]
- Geospatial services companies drove $1.6 trillion in revenues throughout the U.S. economy.
- The industry contributed $1.4 trillion in cost savings to the economy.
- Consumers (households) believe they receive $37 billion per year in value above what they pay for devices, applications and access. (This is what economists call consumer surplus.)

GEOBUIZ study

The GEOBUIZ Geospatial Industry Outlook and Readiness Index, 2018 edition, [75] estimated that North America had:

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[72] Boston Consulting Group, "Geospatial Services: A $1.6 Trillion Growth Engine for the U.S. Economy, BCG, June 2012 http://www.bcg.com/documents/file109372.pdf and Boston Consulting Group, "Putting the U.S. Geospatial Services Industry On the Map," slides, BCG, December 2012 http://education.nationalgeographic.com/media/file/BostonConsultingGroup_U.S._FullReport.pdf

[73] Hickling Arthurs Low, et. al., *Canadian Geomatics Environmental Scan and Value Study, Summary Report*, Prepared for Natural Resources Canada, 2016 http://ftp2.cits.rncan.gc.ca/pub/geott/ess_pubs/296/296426/cgdi_ip_41e.pdf

[74] In contrast, the American Society for Photogrammetry and Remote Sensing assessed remote sensing revenue alone as $7 billion in 2010 based on its Gross Revenue Survey of members. See American Society of Photogrammetry and Remote Sensing, "ASPRS Ten-Year Remote Sensing Industry Forecast, Phase IV," *Photogrammetric Engineering and Remote Sensing* (November 2011), pp.1081-1095 http://onlinedigitalpublishing.com/publication/?i=86396

[75] Geobuiz, *Geospatial Industry Outlook & Readiness Index*, 2018 edition https://geobuiz.com/geobuiz-2018-report.html

- A 25.7% global market share in the GNSS and positioning market, with a 9.7% trend rate of growth.
- A 43.2% global market share in GIS/spatial analytics, with a 7.7% trend rate of growth.

Canadian Geomatics Environmental Scan and Economic Value Study

Natural Resources Canada's Mapping Information Branch, in collaboration with the Canada Centre for Remote Sensing and the Surveyor General Branch, commissioned a study by Hickling Arthurs Low in partnership with ACIL Allen Consulting, Fujitsu Canada and ConsultingWhere.[76] The purpose of the study was to examine:

- The state of the geomatics sector in Canada
- Global trends involving geospatial information and Canada's position relative to those trends
- The significance and value of the geomatics sector and geospatial information to the Canadian economy
- The current new and alternative roles for government, industry and academia in driving, supporting and using geospatial information

The study reported both direct and impacts multiplied throughout the economy:

- Firms in the private geospatial sector contributed C$2.3 billion to Canada's GDP in 2013 (2.44 USD) The sector includes location-based services, broadly defined.

- Geospatial information use resulted in C$20.7 billion in additional GDP in 2013 (22.0 USD) , 1.1% of GDP, and contributed 19.6 million additional jobs and a C$2.8 billion (3.0 USD) increase in the net trade surplus. The Canadian GDP value is based on a multiplier of 9 for which is much larger than has been used in other studies.

- The study identified 2,454 private sector establishments with 115,054 employees in all occupations providing geomatics products and services in Canada. It estimated that 22,504 geospatial jobs were in those firms and 19,577 full time equivalent jobs were added to the economy as a result of geospatial information use.

> If the U.S. geomatics industry was 9.1 times the size of only the Canadian *private* geospatial sector as was GDP in 2013, its size would have been $22.2 billion in 2013. If it then grew at the rate of nominal U.S. GDP, the size of the U.S. geomatics industry would have been $27.1 billion in 2018.

If the U.S. geomatics industry was 9.1 times the size of only the Canadian *private* geospatial sector as was GDP in 2013, its size would have been $22.2 billion in 2013. If

[76] Hickling Arthurs Low, *et. al.*, *Canadian Geomatics Environmental Scan and Value Study, Summary Report*, Prepared for Natural Resources Canada, 2016 http://ftp2.cits.rncan.gc.ca/pub/geott/ess_pubs/296/296426/cgdi_ip_41e.pdf and Hickling Arthurs Low, *et. al.*, *Value Study Findings Report*, prepared for Natural Resources Canada, 2016 https://geoscan.nrcan.gc.ca/starweb/geoscan/servlet.starweb?path=geoscan/fulle.web&search1=R=297711

it then grew at the rate of nominal U.S. GDP, the size of the U.S. geomatics industry would have been $27.1 billion in 2018. This is an underestimate of the USD national size since it is based on the Canadian private sector.

The estimated size of the U.S. geomatics industry based on Canadian study of the private sector of $27.1 billion in 2018 compares with the estimate based on U.S. occupation data of spending of $22.1-$30.4 billion.

If the contribution of geospatial information to the U.S. economy was 9.1 times the geospatial sector's overall contribution in Canada it would have been $200 billion in 2013 and $244 billion when updated to 2018 based on changes in GDP. However, the Canadian study uses a very high multiplier of 9.
If instead the contribution of geospatial information to the U.S. economy based on the Canadian data was multiplied 1.5-2.0 times the geospatial sector size which is consistent with multipliers used in other studies, the geospatial sector's U.S. impact, including its direct contribution, would have been $40.7-$54.4 billion in 2018.

US GDP was 9.1 times Canadian GDP in 2013. Assuming the number of jobs in the U.S geospatial industry was 9.1 times the number of private Canadian geospatial jobs, the number of U.S. jobs in geospatial industry would have been 204,786 in 2013. This is an underestimate of what is implied by the Canadian study for overall U.S. jobs in the sector since the Canadian study only included private sector jobs, but it is higher than the actual estimate of U.S. geospatial jobs in the present study.

2012 Economic Census

Revenue of private surveying and mapping firms in 2012 was $4.6 billion in geophysical surveying and mapping and $5.8 billion for firms in other surveying and mapping, a total of $10.4 billion. Revenue of firms in the industries include products other than surveying and mapping and geophysical surveying and mapping.

Data from the 2017 Economic Census is scheduled to be released over a two-year period beginning in September 2019 and will not use the same industry definitions as previous Economic Censuses.

Methods of Estimating Socio-Economic Benefits

Types of Measures of Benefits

Expenditures and other indications of scale can provide a general gauge of the importance of programs, users and uses. However, they do not provide a measure of incremental value of a program. To determine socio-economic impacts, it is necessary to examine outcomes and to associate values with those outcomes.

Many possible measures of benefits might be considered. These include:

- Changes in the availability, scope and quality of services
- Changes in productivity and/or reductions in costs, or avoided costs
- Changes in fatalities and disability
- Changes in property loss or loss in the value of property
- Changes in insurance rates
- Willingness-to-pay or willingness to receive payment for particular outcomes (Where willingness-to-pay is used, consumer surplus is included.)
- Value of time saved
- Value of environmental changes
- Consumer surplus which measures value to users above their costs
- Producer surplus which measures value to businesses above their costs
- Improvement in or reduction in deterioration in the environment
- Value of reduction in risk

The primary focus in this study is on benefits in the form of cost savings and avoided costs because of availability of information. Note that productivity increases and cost savings are two sides of the same coin since the need for fewer resources can permit producing more with the same amount of resources as previously or producing the same amount at a lower cost.

In some applications the availability of more accurate orthometric heights can result in calls for additional work (cost) to get the desired greater accuracy. This can occur because the level of accuracy was previously not correctly known and was much poorer than required. However, reduction in costs is likely to be far more common.

For some applications improved orthometric heights can contribute to reducing fatalities and injuries. Estimates are made for two cases for which there is evidence from other studies.

It is desirable to include values for environmental benefits. However, while environmental benefits can be very important, measures of impacts of improved height measurement are not generally available at a broad level or for applications of interest.

Approach to Benefit Estimation

Benefits are measured by comparison with outcomes that would have been expected in the absence of the program. Benefit estimates are gross in that they do not adjust for changes in costs to users in making use of the improved orthometric heights or transitioning to the new datum.

The analysis of benefits is for the U.S., including its territories, and does not include direct or indirect benefits to other nations or to global measurement.

Estimating Economic Benefits

Estimates differ in their inclusion of applications of improved orthometric heights because of the nature of the information available. Ways in which improved height measurement may achieve benefits are discussed in the footprint analysis.

In estimating economic benefits, rough adjustments are made where appropriate to allow for benefits attributable to the use of alternative technologies. Benefit estimates also reflect rough adjustments to reflect the combined impact sources of improved orthometric heights other than the Gravity Program.[77]

The preliminary value of the Gravity Program incorporates information from the footprint analyses, examination of the nature of benefits, review of existing studies, analyses from NGS, expert opinion, external data, and economic and statistical methods that depend on the nature of the data.

Assessing the socio-economic value of improvements in outcomes starts with analyzing the 1998 National Height Modernization Study.[78] Local benefits of the extent of improvement in height measurement with orthometric heights derived from the Gravity Program based on GRAV-D are noted in the NGS Geoid Slope Validation Surveys. The analysis then considers the possible value of improvements in particular applications based on a number of studies and relies on expert opinion for an estimate based on cost savings experience for geospatial activities with an experimental geoid.

Approximate economic multiplier effects are incorporated selectively to illustrate impacts on other parts of the economy. This is done based on adapting multipliers that have been used in other studies, using a low value to illustrate a minimum magnitude of multiplier effects.

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[77] These include activities of users requiring more precise elevations than provided by the Gravity Program which are obtained from their own gravimeters or those of consultants and services of commercial providers that substitute for activities of the Gravity Program.
There is no need for an adjustment for services that California provides for itself because they are additions to what NGS provides rather than substitutes for it. California takes the NGS data and changes the epochs, for example if there is a major earthquake or flood. They use the same tolerances as NGS, but the absolute position can change by a couple of feet because data points are added to address local and regional problems.

[78] Dewberry & Davis and Psomas & Associates, *National Height Modernization Study: Report to Congress*, Washington, DC: National Oceanic and Atmospheric Administration, National Geodetic Survey, June 1998 https://www.ngs.noaa.gov/PUBS_LIB/1998heightmodstudy.pdf

Estimates of potential benefits are made for 2019 and extrapolated. It will take many years for the modernized system for height measurement to be adopted widely. Scenarios used in estimating possibilities of future benefits are informed by judgements about the historical pace of adopting new reference frames and market considerations. Present discounted values of streams of future benefits are calculated for each of the scenarios to provide total measures of the value of the NGS Gravity Program.

Estimating Employment Effects

The NGS Gravity Program can result in either increases or decreases in jobs. The first-order effect of cost savings or productivity increases can be a reduction in jobs. The lower cost also may increase demand for products or activities that use the services and result in the addition of jobs. For surveying and associated activities, the expansion of demand due to lower cost may be small since requirements of projects that use the services often may be fixed and activities that take advantage of the new geopotential datum may represent a small part of overall project cost. However, increased capabilities may lead to creation of new applications which can result in expansion. Net effects of cost changes and production and market changes may be too conjectural to quantify with the available data but overall impressions can be provided.

Safety-of-Life Benefits

Standard economic methods are available to place values on lives saved. Numerous discussions of these methodologies have been published.[79]

The benefit of preventing a fatality is measured by the Value of a Statistical Life (VSL). VSL has traditionally been defined as the amount individuals would be willing to pay on average to avoid risks that in the aggregate would result in one death. VSL is based on examining values people attach to small changes in probabilities of loss of life, measured by differences over a large population. VSL is not a measure of the worth of the individual.

The value of an injury is sometimes stated as a fraction of VSL, with greater fractions for more severe injuries. For present purposes, as an approximation, injuries are valued at one-tenth of those of fatalities.

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[79] U.S. Department of Transportation, Office of the Secretary, "Guidance on Treatment of the Economic Value of a Statistical life in U.S. Department of Transportation Analyses – 2016 Adjustment," in "Economic Analysis," memorandum from Molly J. Moran and Carlos Monje, August 8, 2016 https://cms.dot.gov/sites/dot.gov/files/docs/2016%20Revised%20Value%20of%20a%20Statistical%20Life%20Guidance.pdf, U.S. Department of Transportation, National Highway Traffic Safety Administration, *The Economic and Societal Impact of Motor Vehicle Crashes, 2010*, DOT HS 812 013, May 2015 (revised) http://www-nrd.nhtsa.dot.gov/pubs/812013.pdf , U.S. Department of Transportation, Federal Aviation Administration, "Treatment of Values of Life and Injury in Economic Analysis," September 2016 https://www.faa.gov/regulations_policies/policy_guidance/benefit_cost/media/econ-value-section-2-tx-values.pdf , Wilhelmine Miller, Lisa A. Robinson and Robert S. Lawrence (eds.), *Valuing Health for Regulatory Cost-*Effectiveness Analysis, National Academies Press, 2006 http://www.nap.edu/catalog/11534/valuing-health-for-regulatory-cost-effectiveness-analysis

Averted fatalities are valued at $5-$10 million each which includes a lower value and a higher value which is in the range used by government agencies.[80,81]

The value of an injury is sometimes stated as a fraction of VSL as an overall approximation to estimates that take into account severity of injury. For present purposes injuries are valued at one-tenth of those of fatalities.

Environmental Benefits

A large number of environmental impacts are possible, including effects on water quality, coastal erosion, health of ecosystems, perpetuation of marine life, etc. Their importance and nature can vary greatly among geographies and circumstances. Some measures of outcomes or valuation apply only under very specific conditions. Available studies to draw on may be so limited, narrow in scope or disparate that they cannot easily be encapsulated or may require technical expertise that can only be provided in a more specialized and extensive analysis. Estimates for individual cases may not be representative of national benefits. Available time and resources do not permit overcoming these limitations.

Are There Diminishing Returns to Improvement in Geoids?

One can speculate as to whether the great advances in measurement of orthometric heights in the past means that smaller gains are possible in the future or whether improved measurement and availability of orthometric heights and further technological advancement will result in gains that are as large or larger in their impacts than those of the past.

- The argument for lower gains is that the shift to use of the NAVD 88 together with GNSS garnered such a large improvement that it is unlikely to be surpassed with the improvements planned for 2022, especially because a geoid was first provided with NAVD 88 and made a large difference.

- The argument for believing that the value of benefits of the NGS Gravity Program can be as great or greater than those of improvements over the last two decades is that the new improvements in accuracy of orthometric heights will be large and will be available almost anywhere at a much lower cost. This will occur in a much larger economy and much more

[80] Federal agencies have raised the values assigned to loss of life rapidly. See Dave Merrill, "No One Values Your Life More than the Federal Government," bloomberg.com, October 19, 2017 https://www.bloomberg.com/graphics/2017-value-of-life/ Values used by U.S. government agencies are much higher than those used in other countries.

[81] For a review of estimates see U.S. Executive Office of the President, The Council of Economic Advisors, *The Underestimated Cost of the Opioid Crisis*, November 2017 https://www.whitehouse.gov/sites/whitehouse.gov/files/images/The%20Underestimated%20Cost%20of%20the%20Opioid%20Crisis.pdf Values for VSL are much lower in Europe than in the U.S. For a critique of values used by U.S. government agencies see Dave Merrill, "No One Values Your Life More than the Federal Government," bloomberg.com, October 19, 2017 https://www.bloomberg.com/graphics/2017-value-of-life/

technologically complex society that is highly reliant on precise information and an environment in which understanding many of many of the applications has taken on greater urgency.

Regardless of whether the reductions in costs or other benefits are smaller or larger than those achieved earlier, there are great opportunities for gains that have a large impact on a wide range of activities.

The 1998 National Height Modernization Study

Findings of the 1998 Study

The 1998 National Height Modernization Study Report to Congress[82] is a comprehensive and detailed expert analysis of the value of relying on GPS-derived heights over traditional leveling that has proven very useful through the years. The study is examined with a view toward obtaining information that can be used in assessing benefits from the much more precise height measurement with the NGS Gravity Program.

The 1998 National Height Modernization Study estimated cost savings and other benefits from improvements over traditional leveling with the use of GPS and NAVD 88. Sixteen case studies conducted for the study included post-analysis of pre-existing studies and ad-hoc height survey projects to compare GPS with traditional methods. Diverse applications were included. Focusing on variable costs in field operations, the study 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."[83]

The study's summary ranges for the percentage savings in variable costs from the case studies are shown in Table 11. Costs refer to costs of field work and do not include costs of equipment and back office processing.

Table 11. Variable Cost Savings from GPS in the 1998 National Height Modernization Study

Application	Saving
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%

Source: Dewberry & Davis and Psomas & Associates, *National Height Modernization Study: Report to Congress*, June 1998, p.xx https://www.ngs.noaa.gov/PUBS_LIB/1998heightmodstudy.pdf

[82] Dewberry & Davis and Psomas & Associates, *National Height Modernization Study: Report to Congress*, Washington, DC: National Oceanic and Atmospheric Administration, National Geodetic Survey, June 1998 https://www.ngs.noaa.gov/PUBS_LIB/1998heightmodstudy.pdf
[83] *Ibid*., p. xix.

While the appropriateness of using variable cost is not made explicit, variable costs may provide a useful approximation to incremental costs for the set of applications as a whole. However, if costs other than for field work for some applications do not decline by as large a percentage as field operation costs as a result of the use of GPS or if they increase, variable cost of field operations will overstate the percentage decline in total costs.

While variable costs probably do overstate the overall percentage of reduction in incremental costs somewhat across all of the applications, applications can achieve additional benefits such as greater certainty (reduced variance) and shorter project completion times that allow better scheduling of other resources and longer use of end projects. Thus, while cost savings may be underestimated, the error may be offset to some extent by not including benefits other than reduced costs.

Cost savings were found to increase dramatically with increased distance covered, as can be seen in the variable cost savings for applications such as water district elevation surveys and topographic mapping for reservoir construction in Table 11, as well as in the overall savings with distance in Table 12. Also, cost savings were found to be larger and start at earlier distances for the more complex survey types.

Table 12. Variable Cost Savings from GPS According to Distance in the 2008 National Height Modernization Study

Baseline length	Two points connected by a single baseline	Four new points of a box forming multiple baselines
1 km	-138%	-19%
2 km	-19%	40%
3 km	21%	60%
4 km	40%	70%
5 km	52%	76%
10 km	76%	88%

Source: Dewberry & Davis and Psomas & Associates, *National Height Modernization Study: Report to Congress*, June 1998, pp.xxi-xxii
https://www.ngs.noaa.gov/PUBS_LIB/1998heightmodstudy.pdf

Dollar values of benefits are shown in the second column of Table 13. The estimates for the first 5 categories were based on cost savings expected with improved Digital Elevation Models (DEMs).[84,85] Since improved orthometric heights benefit other uses besides DEMs, these estimates understate the benefits of use of GPS.

[84] The study did not include an estimate for the surveying industry which refers to benefits to the industry itself. Benefits to the surveying industry might include higher wages from increased productivity and greater profits for surveying and engineering consulting firms.

[85] Cost savings if NDGPS had been available are also estimated in the study. These are based on a study of NGDPS benefits: U.S. Department of Transportation, *Nationwide DGPS Report*, March 24, 1998
https://www.navcen.uscg.gov/pdf/ndgps/ndgpsESC/NDGPS_PIT_Cost_Benefit_Report_1998.pdf
Safety-of-life and environmental benefits are discussed but their values are not determined.

Table 13. Value of Benefits of a Modernized National Height System through DEMs from the 1998 National Height Modernization Study

Applications Benefitting from a Modernized National Height System	Estimated Value to Constituents (in about 1997)	Explanation of Benefits
Nationwide terrain	$33.5 million	Replace less-accurate Level 1 DEMs that cost USGS $33.4 million Enable rapid generation of contours for USGS maps and GIS nationwide Enable 3-D modeling by USACE, FHA, FRA, FAA, EPS, 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 hydrologic modeling by FEMA to determine depth and extent of flood waters
Coastal Erosion Zones	$11.25+ million	Accurate determination of coastal erosion 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 runoff and stream contamination
Maritime navigation and safety	$9.6 billion	Position of dredges Position of cargo ships
Surveying industry	not estimated	Vastly improved survey procedures
Total excluding maritime navigation and safety	*$2.6+ billion*	
Total excluding farm lands	*$10.5+ billion*	
Total excluding maritime navigation and safety and farm lands	*$870+ million*	
Total	**$12.2+ billion**	

Source: Dewberry & Davis and Psomas & Associates, *National Height Modernization Study: Report to Congress*, June 1998, p.xviii https://www.ngs.noaa.gov/PUBS_LIB/1998heightmodstudy.pdf

The estimates are for potential benefits which are assumed to reach 100% of potential over 15 years. The assumption of 100% adoption in 15 years may be optimistic because: 1) some users would not have had the right conditions to use current or future versions of the technologies, 2) some may not have had or acquired necessary skills, and 3) considerable inertia would have been likely resulting from legal factors, costs, and the need for historical comparability.

The estimates are shown without discounting, i.e. they are determined by adding the values for each year. If they had been discounted by 7% as OMB recommends they would be much lower.

Fully $11.3 of the $12.2 billion in benefits were for marine navigation and farm lands and only $870 million for the rest, with maritime navigation at $9.6 billion and farm lands $1.7 billion. The maritime navigation figure includes positioning dredges and ships. The farm lands figure includes precision farming and control of unwanted runoff and stream contamination. The maritime and farm estimates are examined more closely in the next sections.

Marine Navigation

The 1998 study was not able to provide a direct estimate of the potential benefits of a modernized system for marine navigation. Instead it cited an unofficial estimate of representatives of the maritime industry 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.”[86]

Tax revenue was summed over the projected 15-year life of NDGPS without discounting, resulting in a benefit estimate of $9.6 billion. The tax value discounted at 7% per year would have been $5.8 billion.

The use of a 15 year lookahead contrasts with the use of 10 years for the other estimates. If the first 10 years had been used, the increased tax payments without discounting would have been $6.4 billion instead of $9.6 billion and with discounting at 7% over 10 years they would have been $4.5 billion.

The tax revenue estimate of $640 million per year compares with the finding of the Martin Associates study of U.S. deep water ports that 2007 federal and local taxes paid were $8.3 billion on net economic output of $71.1 billion. Similar results were found in the Martin Associates follow-up study for 2014.[87] With an increase of $640 million per year, improved height measurement alone would have raised shipping tax revenue by perhaps 8% based on 1997, the year before the height modernization study.

While improved elevation measurement could have led to significant reductions in costs which are not taken into account in increased cargo, there also could have been substantial additional costs of enabling the increased cargo.

[86] *Ibid*., p.3-15. The estimate was used despite the height modernization study noting that NDGPS was not being used for maritime elevations.

[87] Martin Associates, *The 2014 National Economic Impact of the Coastal Port System*, Prepared for the American Association of Port Authorities, March 2015 http://aapa.files.cms-plus.com/PDFs/Martin%20study%20executive%20summary%20final.pdf and Martin Associates, *The Local and Regional Economic Impacts of the U.S. Deepwater Port System,2007*, prepared for the American Association of Port Authorities, June 6, 2008 http://aapa.files.cms-plus.com/PDFs/MartinAssociates.pdf The estimates cited do not include multiplier effects.

Farm Lands

The farm lands category is defined in the 1998 study as "precision farming for planned application of water, fertilizer, etc." plus "control of unwanted run-off and stream contamination." While many precision farming applications are mentioned, there is no attempt to distinguish which would benefit from improved vertical measurement or the extent to which alternative technologies might be deployed instead.

The derivation of the $1.7 billion figure in potential benefits for farm lands is not clearly explained. The estimate is described as the result of the combination of DEMs and NDGPS. The Height Modernization Report states: "Over the projected 15-year life-cycle of NDGPS, estimated agriculture potential benefits total $3.436 billion."[88] The NDGPS study found farm benefits of $1.8 billion discounted over 15 years.[89] The estimate from the NDGPS study includes benefits of horizontal as well as vertical measurement.[90] The NDGPS study estimate applies to large farms that can utilize precision farming techniques, which refers to a portion of crops and not fruits, vegetables, nuts rather than to all agriculture.

Update of 1998 Height Modernization Study Estimates for Five DEM Applications

A rough estimate is made of benefits for five DEM applications based on the 1998 National Height Modernization Study. The total is compared with the broader estimate based on the 2012 Dewberry study in the next chapter.

Table 14 shows the potential benefit estimates for the five categories in the 1998 National Height Modernization Study that were based on cost savings from shifting to high accuracy Digital Elevation Models with LiDAR and/or IFSAR.[91] They include a range of activities of USACE, FEMA, NWS, NRCS and several other federal agencies, along with local planning and stormwater management efforts. Substantial savings were to come from avoiding the need for costly photogrammetric contouring of quad maps.[92]

The estimates are updated for changes in nominal GDP between 1997 and 2018, which raised each by 139%. Nominal GDP includes the effects of both inflation and economic growth. Updating with GDP is

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[88] Dewberry & Davis and Psomas & Associates, *National Height Modernization Study: Report to Congress*, Washington, DC: National Oceanic and Atmospheric Administration, National Geodetic Survey, June 1998, p.3-34 https://www.ngs.noaa.gov/PUBS_LIB/1998heightmodstudy.pdf

[89] U.S. Department of Transportation, *Nationwide DGPS Report*, March 24, 1998 https://www.navcen.uscg.gov/pdf/ndgps/ndgpsESC/NDGPS_PIT_Cost_Benefit_Report_1998.pdf It is possible the Height Modernization Study took agriculture benefits for the first 10 years from the NDGPS study and expanded them to allow for the portion of the nation that wasn't covered by the NDGPS expansion that was measured. However, that does not appear to result in the $1.7 billion that was reported.

[90] There is no indication that the benefits adapted from the NDGPS study in the height modernization study were reduced to include only the benefits of precision farming that were attributable to elevation measurements. If $1.7 billion was used instead of $3.4 billion to attribute a portion to height measurement it would be high.

[91] Dewberry & Davis and Psomas & Associates, *National Height Modernization Study: Report to Congress*, June 1998 https://www.ngs.noaa.gov/PUBS_LIB/1998heightmodstudy.pdf

[92] *Ibid*., p.6.3.

more appropriate for the total than for each of the applications but is shown for each for purposes of illustration. The updated total is about $1.6 billion.

Table 14. Value of Benefits for DEMs with GPS from the 1998 National Height Modernization Study Updated to 2018 Based on Changes in Nominal GDP

Applications Benefitting from Improved Digital Elevation Models (DEMs) in 1998 Height Modernization Study	Estimated Value to Constituents (in about 1997)	Value of Benefits Updated to 2018 based on Change in Nominal GDP
Nationwide terrain	$33.5 million	$80.1 million
Nationwide watersheds	$100 million	$239.0 million
Special Flood Hazard Areas (SFHAs)	$225+ million	537.8+ million
Coastal Erosion Zones	$11.25+ million	$26.9+ million
Urban areas	$500 million	$1.2 billion
Total	**$870+ million**	**$1.6+ billion**

Note: Based on cost savings with the use of NAVD 88.
Source: Dewberry & Davis and Psomas & Associates, *National Height Modernization Study: Report to Congress*, June 1998, p.xviii
https://www.ngs.noaa.gov/PUBS_LIB/1998heightmodstudy.pdf and author's calculations.

To estimate the benefits of the Gravity Program for the five Digital Elevation Map applications, benefits are assumed to be 25%-50% of those from the introduction of NAVD 88, or $400-$800 million per year. This includes reduced costs of producing much higher accuracy maps than commonly in use. It allows for the use of technologies that don't depend on orthometric height measurement for some precision farming applications and the slow pace of adoption of many precision farming techniques.

Preliminary Estimates of the Value of the NGS Gravity Program

Some Considerations in Making the Benefit Estimates

The introduction of GPS and NAVD 88 resulted in the potential for large improvements in measurement of orthometric heights as detailed particularly in the 1998 Height Modernization Study. Since that time advances in GNSS and surveying technology, guidelines and practices have added to that potential. The NGS Gravity Program will create further opportunities for large gains.

The greatest benefits are expected from projects covering large geographic areas. The Gravity Program will mean transitioning from an environment in which accuracy is poorer and the degree of accuracy is not well known to one in which accuracy is greater and the degree of accuracy is known. This will reduce the need for repeat measurements and the likelihood of further costs and difficulties later on in the life of a venture.

Benefits will be especially large for projects involving water because gravity is used to determine the direction water will flow and the new orthometric heights will be better aligned with sea level. When combined with data such as geodetic coordinates, ocean, wind and storm surge information and models, height information can also indicate the rate at which water will flow and how far inland it will go. Improved measurement of orthometric heights can be critical in areas with significant subsidence, uplift, flooding, or undulation. It can be used to select sites for large construction projects that pose less risk of costly or dangerous damage from nature. Examples include avoiding the costly subsidence of tracks for the high speed rail in the Central Valley of California which might have been located elsewhere with better elevation measurement, [93] and subsidence of dams or canals that, without accurate heights, can result in insufficient water flow. In the future, precise elevation data can make an important contribution to building or enhancing infrastructure so it can be sustained despite climate extremes.

> Benefits are measured by comparison with outcomes that would have been expected in the absence of the program.

The analysis of benefits is for the U.S. including its territories and does not include direct or indirect benefits to other nations or to global measurement. Benefits are measured by comparison with outcomes that would have been expected in the absence of the program.[94] Benefit estimates are gross in that they do not adjust for changes in

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[93] Amy Quinton, "That Sinking Feeling: Valley Land Subsidence Poses Problems for Water, High Speed Rail," Valley Public Radio, November 21, 2013 https://www.kvpr.org/post/sinking-feeling-valley-land-subsidence-poses-problems-water-high-speed-rail

[94] The NGS Gravity Program can be thought of as improving height measurement by providing:

1. Updated data to the present with previous methods
2. Improvement over measures used earlier
3. Updates for future geological changes

The Geoid Slope Validation Surveys compare airborne measurements with currently available ground measurements. They do not indicate the improvement from updating orthometric heights to the present without new methods. It has been suggested that those improvements would have been small compared with improvements with the Gravity Program. A separate estimate is not made for these.

costs to users in making use of the new NSRS or in transitioning to it. Ranges are provided around some estimates to suggest levels of uncertainty.

While it is recognized that there are many ways the Gravity Program can improve outcomes and well-being, most of the evidence relates to cost savings or cost avoidance. For example, LiDAR and IFSAR use orthometric heights to position for contour accuracy. Improvements in orthometric heights can permit more accurate positioning as well as reduce the cost of obtaining precise positioning. However, data on the extent to which an improved geoid model can improve the positioning of LiDAR is scarce and reliance here is on cost savings.[95]

Two alternative estimates of benefits are made.

- **Method 1** is based on the cost of surveying and other geospatial activities that was derived by building on occupation data. 50% is taken to exclude work done using other technologies, work done at distances at which geoids do not provide an advantage, and work in the included occupations that is unrelated to orthometric height measurement.

  Subcategory estimates are also shown which are independent of the overall Method 1 estimate and are not combined into a total. These include reduced costs of long line leveling and for FEMA floodplain mapping under the National Flood Insurance Program which replace the estimates in the 2009 study of benefits of CORS and GRAV-D. A rough estimate of the Gravity Program's contribution to benefits of the NWS river and flood forecasts is made based on updates of an earlier National Hydraulic Warning Council study.

- **Method 2** is a hybrid that updates benefit estimates for five applications based on reduced costs of high accuracy digital elevation models (DEMs) with GPS that were developed in the 1998 Height Modernization Study. These include a range of activities of USACE, FEMA, NWS and several other federal agencies along with local planning and stormwater management efforts. Method 2 also replaces the 1998 study's values for agriculture and marine navigation with new estimates. The marine navigation estimate is not limited to DEMs. Estimates are included where possible and do not constitute a complete list of applications.

Next, direct benefit estimates are made for the two methods. Direct benefit estimates are before including economic multiplier effects that incorporate indirect and induced effects on the rest of the economy. Benefits for some of the applications that are implicitly included in Method 1 are then discussed but are not added to produce the total. For Method 2, the overall value is the sum of

[95] Nicole Kinsman, the NGS Regional Geodetic Advisor for Alaska, presented results of a test study for a narrow geographic area at the NGS 2019 Geospatial Summit in Silver Spring, MD on May 7, 2019. Using an experimental geoid, she showed a large difference for a small portion of the test area for water flow. Use of the final geoid is expected to show greater improvement. There is no indication of whether the results are representative of other sites or applications. In the absence of data, the exercise assumes that proportional benefits of the Gravity Program for LiDAR are equal to those of other technologies. See https://geodesy.noaa.gov/geospatial-summit/index.shtml

those component applications examined. Estimates are based on conservative assumptions. Safety-of Life benefits are considered for two applications where they could be based on the available studies.

In the following section, direct economic benefits are summarized and economic multiplier effects are added. Subsequently, annual projections are presented under alternative scenarios and present discounted values of the benefit streams are calculated.

Potential Direct Economic Benefit Estimates

Potential benefits are those that would be expected at 100% adoption. The analysis of future benefits considers scenarios for rates of adoption through 10 years. Two methods are used to estimate potential annual benefits. Categories within a method do not overlap but there is some overlap in benefits between categories in the two methods.

Method 1: An Overall Estimate of Direct Economic Benefits for Geospatial Activities

Some survey and engineering firms have been taking advantage of the availability of GEOID12, GEOID12A and GEOID12B to obtain accuracies that are closer to what they expect to obtain with the NAPGD 2022 geopotential datum being developed drawing on data from the NGS Gravity Program. Without the latest geoids they would have to continue to tie results back to bench marks, with surveying and mapping that is more costly than geodetic leveling.

Based on the experience of an expert outside of NGS with a view across multiple large projects, the costs for infrastructure work without the final geoid would be higher by 30%-50%, which translates into a cost reduction from the levels before the reduction of 23%-33%. For other applications the costs without the Gravity Program would be higher by 10%-20%, implying a reduction of 9%-17%. Combining these into an assumption for geospatial activities as a whole results in an estimate of cost savings of 11%-19%.

The estimate of 11%-19% in savings does not take into account improvements with final version of the new geopotential datum in 2022 from reduced time in processing that will become possible with the new online tools that take advantage of the datum. It also does not include the potentially large benefits of improved project scheduling that saves on other project resources or the reduction in rework and/or repairs or longer lives of buildings and infrastructure with greater accuracy and certainty about heights. The 11%-19% range is doubled to 22%-38% to roughly include benefits beyond the currently available reduction in the cost of field work.

The 22%-38% range of benefits is applied to the estimate of total spending on geospatial activities in 2019 based on occupation data which was made in the footprint analysis. The occupations included were surveyors, survey and mapping technicians, cartographers and photogrammetrists, geoscientists, except hydrologists and geographers, hydrologists, geographers, and an assumed 12,000 full time equivalent civil engineers doing surveying.

Spending on geospatial activities was estimated at $22.1-$30.4 billion in 2018. Spending is updated to 2019 by the estimated 4.8% change in nominal GDP from 2018 which places it at $23.16-$31.86 billion. It is assumed that 50% of the spending or $11.58-$15.93 billion is in the purview of the Gravity Program. This allows for work done using other technologies, work done at distances at which geoids do not provide an advantage, and work in the included occupations that is unrelated to orthometric height measurement.

…an estimate of direct economic benefits of the NGS Gravity Program for geospatial activities of $1.85-$4.30 billion per year based on 2019 economic activity.

Applying 22%-38% to $11.58-$15.93 billion results in an estimate of potential direct economic benefits of the NGS Gravity Program for geospatial activities of $2.55-$6.05 billion per year at 100% adoption based on 2019 economic activity. In comparison, U.S. spending on structures was $1.4 trillion in 2018. For nonresidential structures alone it was $637 billion.

Three Subcategories of Method 1 for Geospatial Activities

These illustrative subcategories are independent of the overall Method 1 estimate and are not combined into a total.

Long Line Leveling

Long line leveling is a subset of the category "Surveying and Other Geospatial Activities." The 2009 Leveson Consulting socio-economic study of CORS and GRAV-D estimated the economic benefits of the NGS GRAV-D program based on 1) avoidance of costs of long-line leveling, and 2) reduced damage to buildings from better maps to determine vulnerability under the National Flood Insurance Program.[96] Current data and additional information are incorporated in updating these estimates.

The Gravity Program is expected to eliminate the need for long line leveling. Savings from GRAV-D which provides data for the Gravity Program were estimated in the 2009 study based on the cost per km of long line leveling, including the cost of no longer repairing and replacing bench marks for the leveling. Assumptions were made about the proportion of work by survey firms that consisted of long line leveling and about the relative amount of surveying by non-surveying organizations. Allowances were added for consumer surplus – the value to users above their cost, and for societal benefits such as safety-of-life and the environment.

Indications are that at present, some long line leveling is being done by utilities and some is being done by Federal agencies for scientific purposes and for measuring distances over large bodies of water. However, there is relatively little being carried out by state and local governments or surveying firms because of cost and some of the work for state and local governments is being done by students.

For the current calculation, the amount of long line leveling to be replaced as a result of improved orthometric heights is assumed to be half as great as the amount estimated for GRAV-D in the 2009 study. That study estimated 65,000 km of long line leveling was being done per year, half of which is

[96] Leveson Consulting, *Socio-Economic Benefits Study: Scoping the Value of CORS and GRAV-D*, January 2009, p.56 http://www.ngs.noaa.gov/PUBS_LIB/Socio-EconomicBenefitsofCORSandGRAV-D.pdf

32,500 km. A current expert opinion is that it costs $2,000-$3,000 per km, which results in a total cost of $65.0-$97.5 million per year which would no longer be incurred with the availability of improved orthometric heights.

FEMA Floodplain Management Under the National Flood Insurance Program

The "conjectural" estimation of benefits of GRAV-D through floodplain management in the 2009 socio-economic study was based on data on the number of buildings built in flood hazard areas and an estimate of the reduction in damage after flood insurance maps required minimum standards. The remaining possible damage was taken as an indication of the potential for further reduction with improved maps.

Several factors were assumed in combination to offset each other. These included costs of meeting the more stringent construction requirements that would come with data from GRAV-D, the portion of the potential reduction in damage that would have been addressed since the year of the data, the reduction in damage from some future buildings locating outside of vulnerable areas, and some reduction in fatalities and injuries from compliant structures or from decisions to locate outside of vulnerable areas.[97]

New information and developments inform an updated estimate. FEMA's experience does not indicate that orthometric height improvement is associated with changes in the extent of areas that are affected by flood damage. FEMA also found that improvements in maps do not result in net movement of buildings in or movement out of the areas experiencing changes in maps.

Furthermore, a new insurance rating methodology is being developed by FEMA which is more consistent with private insurance practices. Elevation surveys are not a factor in the new methodology. Instead, the requirement is to use the best available sources of information. However, the new requirements apply mostly to new construction and some use of elevation surveys will continue.

FEMA plans to announce new insurance rates in 2020 that allow for the value of property, distance from water and other factors. This could achieve some of the location shifts that would otherwise have occurred as a result of future improvements in height information on floodplain maps.

Existing buildings are not required to improve construction until there is a major loss. Improvements could still be substantial in areas with high rates of growth or with repeat threats of damage, but they would not be as extensive as previously unless there also was a considerable increase in extreme weather and/or flooding.

[97] Leveson Consulting, *Socio-Economic Benefits Study: Scoping the Value of CORS and GRAV-D*, January 2009 http://www.ngs.noaa.gov/PUBS_LIB/Socio-EconomicBenefitsofCORSandGRAV-D.pdf

Significant efforts at reducing vulnerability to damage could occur as a result of voluntary actions by property owners or business tenants that take advantage of the information[98] and by efforts to take into account the information in local laws. These efforts could result in significant benefits.

With improved orthometric heights informed by the NGS Gravity Program, National Flood Insurance Program (NFIP), flood plain maps will no longer be tied to bench marks that may be damaged or outdated. This loss of information will be reduced with aerial mapping which will make use of heights from the Gravity Program, but the availability of the information is likely to be phased in slowly as maps are updated.

The 2009 study estimated the savings from improved floodplain management related to the NFIP at $240 million per year. If comparable benefits would have grown by the percentage change in nominal GDP between 2009 and 2018, they would have equaled $357 million. Allowing for insurance becoming voluntary and more costly for structures with greater vulnerability, along with adjustments to flood information that have been made since 2009 and other factors, additional benefits under the Gravity Program from improved maps instead could be anywhere between $50 million and $200 million based on the 2019 economy.

Also, modest savings are expected in FEMA mapping operations. FEMA spends $400 million per year in mapping. About 15% or $60 million is for elevation mapping, including LiDAR and ground surveys. FEMA estimates that the cost savings enabled by the Gravity Program could be 5%-10% of that or $3-$6 million per year.

Taking all of the factors into account, the combined cost savings from FEMA floodplain mapping and use of the maps is estimated at $110-$180 million per year.

Contribution to Benefits of NWS River and Flood Forecasts

Updated NHWC National Weather Service River and Flood Forecast Benefit Estimates

The 2002 National Hydrologic Warning Council (NHWC) study examined benefits of National Weather Service river and flood forecasts based on data for 1981-2000, with the results stated in year 2000 purchasing power.[99] The study made the following estimates of economic benefits, in part based on updating earlier work:

- Benefits from reservoir optimization in operations of USACE, USBR and others that protect downstream areas were $1.022 billion per year.
- Benefits from NWS forecasts and warnings of snow melt and other long-term flood events were $162 million per year.

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[98] The insurance requirement is generally attached to the owner of the mortgage. For renters it is the renters responsibility. For condos the Association buys the overall insurance while the condo owner ensures the inside.
[99] National Hydrologic Warning Council, *Use and Benefits of the National Weather Service River and Flood Forecasts*, prepared by EASPE, May 2002 http://www.nws.noaa.gov/oh/ahps/AHPS%20Benefits.pdf

- Without NWS, short term forecasts that allowed time for responses such as sandbagging and constructing levees, annual flood damage would be 10% higher or $433 million per year.
- Another $243 million per year in benefits was expected from the use of NWS flood forecasts in the Advanced Hydrologic Prediction Service (AHPS) which was being developed.
- In addition, AHPS was expected to benefit hydropower, irrigation, navigation and water supply by what the authors designated as a conservative $523 million per year.

The total of annual benefit expected was $2.4 billion in dollars in year 2000 purchasing power. This is updated based on the growth in flood damage in the following years. Since flood damage varies greatly from year to year, the average of $15.9 billion in property and crop damage from flash and river floods during 2013-2017 is used based on the NWS National Hazard Statistics.[100,101] This compares with $1.9 billion during 2000 which is near the average of the surrounding years. Multiplying the $2.4 billion benefit estimate in 2000 by the ratio 15.9/1.9 of 8.36 results in a current benefit of $20.1 billion.[102]

The updated benefit total includes benefits of both horizontal and vertical measurement along with other processes and technologies. Orthometric heights provide a basis for more accurate measurement of the heights of bodies of water and with measurement of terrain and modeling, enables determination of how far inland water will flow.

Economic Benefits of Improved Orthometric Heights for NWS River and Flood Forecasts

Estimation of the contribution of improved orthometric is based on the assumption that orthometric heights incrementally accounted for 5%-10% of the $20.1 billion benefit of the programs or $1.00-$2.01 billion.

Improvement in orthometric heights informed by the NGS Gravity Program is assumed to add 30%-40% to the existing benefits of height information or $360-$804 million as a result of the programs considered in the NHWC study.

Safety-of-Life Benefits of Improved Orthometric Heights for NWS River and Flood Forecasts

The number of fatalities from floods averaged 108 per year during 2013-2017 and there was an average of 31 injuries.. The ratio of damages to fatalities during 2013-2017 was 147:1 and the ratio of damages to injuries was 512:1. Dividing the estimated range for improvement in height information by these ratios yields an estimate of averted fatalities with improved height information of 2.4-5.5 and averted injuries of 0.7-1.6.

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[100] The average is heavily influenced by the $60.7 billion of damages in 2017.

[101] The National Hazard statistics understate the dollar values as indicated by comparison with the NOAA Billion Dollar Disaster series and NOAA staff. However, it is more accurate for fatalities and injuries. It is known how the understatement affects the trend in damages.

[102] It is possible that improved forecasts will have their greatest impacts for the least extreme floods because the easiest responses will occur first. Benefits also could be proportionally greater for the least extreme floods if the most severe flooding was hardest to predict. Extreme flooding may be harder to predict, for example, if it was heavily influenced by climate change phenomena that are less well understood than short term developments or knowledge of which is less well integrated into shorter term flood forecasts. It is also possible that there will be proportionally greater impacts when the risk of flood damage is greatest. That could occur if the higher risk induces more extensive use of the information.

With Averted fatalities are valued at $5-$10 million each and injuries at $500,000-$1,000,000, the value of averted fatalities is $24-$55 million and the value of averted injuries is $350,000-$1.6 million. The combined value of averted fatalities and injuries is $24.4-$56.6 million.

Method 2: Sum of Components Component Benefit Estimates

Potential benefits are estimated based on the Dewberry 2012 National Enhanced Elevation Assessment with new estimates for agriculture and marine transportation.[103] The marine transportation estimate includes NOAA's Physical Oceanographic Real-Time System (PORTS®) Program and inland navigation.

Potential Benefits for DEMs Estimated from the 2012 National Enhanced Elevation Assessment

Dewberry Use Case Estimates

The National Height Elevation Assessment conducted by Dewberry and reported in 2012 examined use case accuracy requirements and estimated conservative and potential annual benefits for the portion of 27 applications for which data was available.[104] Five levels of quality consisting of defined specifications of horizontal and vertical accuracy were compared with the current patchwork of data in the National Elevation Database (NED).[105] Benefits were based on extensive interviews with managers in federal, state, and nongovernmental organizations. The use case data which applies to full coverage of the coterminous United States, shown in Table 15, is in 2011 dollars.

Dewberry estimates conservative benefits of enhanced national elevation data for these categories totaling $1.2 billion per year, while potential benefits were $13.0 billion. The total for conservative benefits is understated due to blank entries because 49% of managers were unable to estimate the benefits of activities even though they indicated they were mission-critical.

Potential benefits assume that required quality levels and update frequencies are followed. [106] Those levels are not expected to be fully followed and benefits will be lower than the values designated as potential.

The conservative benefits total of $1.18 billion does not include "marine navigation and safety" which had the largest benefit estimate in the 1998 National Height Modernization Study. Without "agriculture and precision farming" which had the second highest benefits in the 1998 National Height Modernization study, the conservative total is $1.06 billion.

The total of potential benefits of $12.98 billion would be $10.97 billion without agriculture. The agriculture and precision farming potential benefits of $2.0 billion in 2011 compares with potential

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[103] The Dewberry estimates do not include marine transportation.

[104] Dewberry, *National Enhanced Elevation Assessment Final Report*, report on the National Enhanced Elevation Assessment to the U.S. Geological Survey, March 29, 2012 http://www.dewberry.com/docs/default-source/documents/neea_final-report_revised-3-29-12.pdf?sfvrsn=a46dba28_0

[105] *Ibid*, pp.3-4.

[106] *Ibid*., p.6.

Table 15. Estimated Annual Benefits from Enhanced Elevation Data, by Business Use, 2011 (millions of 2011 dollars)		
Business Use	**Conservative Benefits**	**Potential Benefits**
Flood Risk Management	294.7	501.6
Infrastructure and Construction Management	206.2	942.0
Natural Resources Conservation	159.2	335.2
Agriculture and Precision Farming	122.3	2,011.3
Water Supply and Quality	85.3	156.4
Wildfire Management, Planning and Response	75.7	159.0
Geologic Resource Assessment and Hazard Mitigation	51.8	1,066.8
Forest Resources Management	43.9	61.7
River and Stream Resource Management	38.4	86.6
Aviation Navigation and Safety	35.0	56.0
Coastal Zone Management	23.8	41.7
Renewable Energy Resources	10.1	100.1
Oil and Gas Resources	10.0	100.0
Homeland Security, Law Enforcement, Disaster Response	10.0	126.5
Sea Level Rise and Subsidence	5.8	21.7
Urban and Regional Planning	4.2	68.6
Resource Mining	1.7	4.9
Wildlife and Habitat Management	1.5	4.0
Education K-12 and Beyond	0.3	2.3
Land Navigation and Safety	0.2	7,124.9
Telecommunications	0.1	1.9
Recreation	0.1	0.1
Cultural Resources Preservation and Management	0.0	7.0
Health and Human Services	0.0	1.0
Marine Navigation and Safety	0.0	0.0
Real Estate, Banking, Mortgage, Insurance	0.0	0.0
Rangeland Management	0.0	0.0
Total	**$1,180.2**	**$12,980.7**
Source: Dewberry, *National Enhanced Elevation Assessment Final Report*, report on the National Enhanced Elevation Assessment to the U.S. Geological Survey, March 29, 2012, Table 1.3 http://www.dewberry.com/docs/default-source/documents/neea_final-report_revised-3-29-12.pdf?sfvrsn=a46dba28_0 and author's calculations		

benefits of $1.7 billion for farm lands in 1997 in the 1998 National Height Modernization Study (see Table 13). A separate estimate is made for agriculture in the present study.

The $12.98 billion in annual potential benefits also includes $7.12 billion for "land navigation and safety". The land navigation and safety estimate was based on expectations from Tom Tom that starting in 2014, most leading car and truck manufacturers would have introduced automatic transmission control technology based on 3-D road geometry from airborne LiDAR to achieve fuel efficiency between

4% and 14%.[107] This can now be seen as unrealistic and other technologies that do not utilize LiDAR have advanced. Excluding both agriculture and land navigation and safety, the total of potential benefits is $3.85 billion per year in 2011 dollars.

Over $1 billion in potential benefits was reported for geologic resource assessment and hazard mitigation. This plus $942 million for "infrastructure and construction management" makes up half of the $3.85 billion per year in potential benefits excluding agriculture and land navigation and safety.

Overall Dewberry Benefit Estimate

In its extensive analysis, Dewberry was able to estimate benefits for less than half of the functional categories because of incomplete data. The resulting conservative estimate of benefits was $1.008 billion per year before deducting costs. The value used includes potential benefits of synergies between government agencies from national coordination. Even this estimate was considered overstated "because not every functional activity receives exactly the quality level and update frequency required…"[108] However, Dewberry also estimated that the potential for understated and emerging benefits could reach $13 billion in future years when new technologies are implemented, but the study did not use those values in the analysis.

Extension to Estimate of NGS Gravity Program Benefits through Digital Elevation Maps

The $122.3 million Dewberry estimate for agriculture is removed from the $1.008 billion per year total because benefits of the NGS Gravity Program to agriculture are estimated separately. The resulting value of $885.7 million in 2011 is raised to $1.224 billion in 2019 based on the percent change in nominal GDP. To illustrate potential benefits of the NGS Gravity Program, since the Dewberry estimate is so conservative, NGS Gravity Program gross benefits excluding agriculture through DEMs are assumed to be 80%-120% of that value. This assumes that a portion of the higher Dewberry potential benefits is included but offset by actual practice being at less than ideal specifications. At 80%-120%, the benefit of the NGS Gravity Program through improvement in Digital Elevation Maps except for agriculture would be $979 million-$1.469 billion per year.

The $979 million-$1.469 billion estimate of potential benefits based on Dewberry compares with the estimate of $400-$800 million per year for five applications based on updating the findings of the 2008 National Height Modernization Study in the last section of the previous chapter. The estimate based on the Dewberry 2012 report is relied on because the information is more current and more complete.

Benefits of Orthometric Heights for Precision Farming in 2019

Leveson reported: "John Deere estimated that auto-guidance was used in 2011 by 65% of grain farms with $250 million or more in products sold and that it may have increased to 70% in 2014."[109] He estimated $111.5 billion in grain sales net of the value of farm subsidies in farms with sales of $250 million or more. At 65% market penetration, use of auto-guidance for farms with $250 million or more in grain products sold would have been $66.9 billion in 2013.

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[107] *Idem*., p.14.

[108] *Idem*., p.4.

[109] Irving Leveson, *GPS Civilian Economic Value to the U.S., Interim Report*, prepared for the National Executive Committee for Space-Based Positioning, Navigation and Timing, August 31, 2015, p.47 http://www.performance.noaa.gov/wp-content/uploads/2015-08-31-Phase-1-Report-on-GPS-Economic-Value.pdf

Based on a composite of estimates of several studies, Leveson assessed that as of 2013: "Systems utilizing GNSS are estimated to save 10%-15% in operating costs and purchased inputs for grain farming. A composite of estimates of yield increases associated with improved plant health is an additional gain of roughly 8%-10%." Together these constituted a benefit of 18%-25% of grain sales net of the value of farm subsidies in farms using auto-guidance with sales of $250 million or more.[110]

Applying 18%-25% to $66.9 billion in sales of farms using auto-guidance resulted in gross benefits of $12.0-$16.7 billion, of which 60%-70% was assumed to be attributable to GNSS and the rest to alternative technologies. Taking 60%-70% of gross benefits puts the value of GNSS for grain farming using auto-guidance at $7.2-$11.7 billion in 2013. This includes contributions of both horizontal and vertical measurement. If the contribution of vertical measurement with GNSS was one fifth of that it would be valued at $1.4-$2.3 billion.

The U.S. agricultural market has been under great pressure since 2013, with plantings, prices and farm revenue severely impacted. Under these conditions it is assumed that the benefits of any increases in adoption of precision farming techniques utilizing orthometric heights would have been offset by reduced volumes of production and prices, so benefits would at best be unchanged. Consequently, the estimated value of benefit of orthometric height improvement with the NGS Gravity Program for precision farming in agriculture in 2019 is taken as $1.4-$2.3 billion.

Benefits of improvements in orthometric height measurement with the NGS Gravity Program are assumed to be half of the updated benefits from heights that were found to come through the use of GNSS or $700 million-$1.65 billion per year. The estimate is conservative since it does not include use of techniques other than auto-guidance or crops other than grains.

Marine Navigation

The Ports Program®

Description of the PORTS® Program

NOAA's Physical Oceanographic Real-Time System (PORTS®) Program is a decision support tool that disseminates observations and predictions of water levels, currents, salinity, and meteorological parameters for mariners. It is vital for management of vessel movement in and around ports. Orthometric heights are essential in measurement of water levels and currents.

Wolfe notes that: "During 2016, the National Ocean Service's (NOS) Center for Operational Oceanographic Products and Services' (CO-OPS) PORTS® installations were located at ports that handled about 87 percent of international cargo weight and over 81 percent of international cargo value. At

[110] *Idem*., pp.46-47.

these locations, PORTS® covered in excess of 91 percent of containerized vessel tonnage and almost 89 percent of containerized cargo value."[111]

Activity is concentrated among the largest ports. For ships with four feet or less depth under keel, 52% of the value of cargo in U.S. ports comes from the 5 largest ports and 80% from the 13 largest ports.[112]

The Wolfe and MacFarland Studies

Benefits of the PORTS® Program include outcomes resulting from obtaining data from sensors for the program put in the ports, transforming data from those sensors and from other sources into a comprehensive system and distributing the information.

Wolfe and MacFarland found in their 2013 study that the Physical Oceanographic Real-Time System (PORTS®) Program would have had benefits of $141.0 million in year based on data for 2010 for the 58 seaports thought to be participating at the time.[113] (A port can contain multiple seaports.) Calculations were made taking advantage of detailed information on depth from a Channel Port Tool developed by the U.S. Army Corps of Engineers to estimate impacts on cargoes.

Benefits from increased cargo capacity with additional vessel draft were estimated at $119.6 million. An additional $17.3 million in benefits came from largely commercial avoided accidents, including property damage, mortality and morbidity. Benefits also came from oil pollution remediation, increased fish catch, and reduced commercial marine and recreational boating accidents.

Wolfe and MacFarland subsequently revised the benefits in a 2016 article to add $76.4 million for reduced delays in commercial traffic transit.[114] The updated analysis found the value of the PORTS® program for the existing 58 PORTS® to be $217.4 billion based on data for 2010, and that if the program was extended to 175 ports the value would be $300.0 billion annually.

Economic benefits with the existing 58 PORTS® were $205.4 million per year and the value of averted mortality and morbidity losses was $12.0 million. With 175 PORTS® the value of economic losses averted by the program was projected to be $280.6 million per year and the value of averted mortality and morbidity losses was projected to be $19.5 million per year. Note that the value of averted fatalities and

[111] Wolfe, K. Eric, *Vessel Allisions, Collisions and Groundings Incidents: Estimated Impact of PORTS® (2005-2016)*, report, National Ocean Service, National Oceanic and Atmospheric Administration, September 6, 2017.
[112] *Ibid*.
[113] K. Erik Wolfe and David MacFarland, *An Assessment of the Value of the Physical Oceanographic Real-Time System (PORTS®) to the U.S. Economy*, National Oceanographic and Atmospheric Administration, September 13, 2013
http://tidesandcurrents.noaa.gov/publications/ASSESSMENT_OF_THE_VALUE_OF_PORTS_TO_THE_US_ECONOMY.pdf
[114] K. Erik Wolfe and David MacFarland, "A Valuation Analysis of the Physical Oceanographic Real-Time System (PORTS®)," *Journal of Ocean and Coastal Economics*, 2016, p.30
http://cbe.miis.edu/cgi/viewcontent.cgi?article=1058&context=joce

injuries with the PORTS® Program is higher relative to economic gains with inclusion of the smaller ports.

Updating the Wolfe and MacFarland Estimates

The dollar value of U.S. trade increased by 30.7% during 2010-2018. Economic benefits of the PORTS® Program if it had applied to 175 ports is raised by 34% percent from $280.6 million per year to $376.0 million to obtain an estimate for 2019.[115]

Assuming that the value of averted mortality and morbidity would have increased between 2000 and 2019 by the same 34% percent as cargo, the value of averted mortality and morbidity losses in 2019 is projected to be $26.1 million per year.

The 2016 update did not indicate the numbers of deaths and injuries averted, but they can be inferred from the earlier analysis. In the 2003 study the value of averted deaths was 67.24% of the total value of loss from deaths and injuries and the share of the value of averted losses for injuries was 32.76%. Assuming the same percentages apply to the updated value of averted losses from mortality and morbidity of $26.1 million per year, the value of averted mortality is $17.59 million and the value of averted injuries is $8.55 million. Wolfe and MacFarland's used $6.1 million as the value of a statistical life and $0.6 million as the value of an injury in both studies. With a value of $17.59 million, the number of averted deaths in the updated analysis is estimated as 2.88 per year, and with a value of $8.25 million per injury the number of averted injuries is 13.75.

The present study uses $5-$10 million for the value of a statistical life and $500,000-$1 million for the value of an injury. At $5-$10 million the reduced loss from averting 2.88 deaths is $1.44-$2.88 million per year. The value of 13.75 averted injuries at $500,000-$1 million is $6.88-$12.75 million per year. The values ascribed to mortality and morbidity used in the present study are in dollars of year 2019 purchasing power so the values of averted losses are in 2019 dollars.

Benefits of the Gravity Program for Ports

Data for 175 ports provides a basis for estimation of potential economic benefits of the NGS Gravity Program because of the authors' near complete coverage of ports. The estimate of $376.0 million in economic benefits that the PORTS® Program would have if the program applied to 175 ports includes benefits both for currently available horizontal and vertical accuracy. Since a substantial portion of the of the benefit estimate was for greater cargo carriage with increased hull clearance which depends on accurate orthometric heights, available height information is assumed to account for 30%-50% of the benefits for 175 ports or $112.8-$188.0 million per year.

[115] The increase may be conservative in view of the growing importance of PORTS® for large ships. The World Shipping Council noted that recently container ships of roughly 12,000-14,000 TEUs had begun calling on California ports. The new locks of the Panama Canal which opened in mid-2016 allow passage of container ships up to 13,000 TEU. American Association of Port Authorities http://www.aapa-ports.org/unifying/content.aspx?ItemNumber=21048#Statistics http://www.marad.dot.gov/wp-content/uploads/pdf/US_Water_Transportation_Statistical_snapshot.pdf

Improved orthometric heights with the datum informed by the NGS Gravity Program are assumed to raise the existing benefits of height information for ports by 15%-25% or $16.9-$47.0 million. The same percentage is assumed for mortality and morbidity. The result is 0.158-0.360 averted deaths per year with improved orthometric heights and 0.776-1.763 averted injuries per year. These are valued at $79,000-$360,000 for averted fatalities and $378,000-$1.59 million for averted injuries.

Drayage

Drayage refers to the movements of goods off and on ships and to rail and trucking facilities. Vertical control is used to understand and plan for risks to drayage associated with subsidence and flooding from storms and sea level rise. A separate estimate is not made for this.

Inland Waterways

Inland waterways of the United States include more than 25,000 miles (40,000 km) of navigable waters. A National Waterways Foundation study in 2014 estimated the value of inland waterways in 2012 using an abandonment scenario which considered the additional costs of using the next best transportation alternatives and included impacts on affected industries (multiplier effects). The loss from unavailability of inland waterways during the first year was $124.2 billion. Later years in the National Waterways Foundation scenario showed somewhat larger losses from abandonment.[116] The first-year number is used to be conservative.

The study's inclusion of economic multiplier effects is removed to obtain direct benefits consistent with the other first step estimates in the present study. Direct benefits of inland waterways are taken to be 40% of first year benefits or $49.7 billion. Updating this value from 2012 to 2019 by the change in nominal GDP to take into account inflation and economic growth raises the value to $60.9 billion**.** This includes the impacts of all of the years of construction and the evolution of operations and maintenance, with activities taking place using different datums at different times.

Annual operations are assumed to be valued at 8%-10% of the abandonment loss or $4.88-$6.09 billion per year. For the purposes of illustrating possible magnitudes, direct benefits of orthometric heights are assumed to equal 2%-3% of the value of annual operations or $97.6-$182.7 million per year. If improvements in height measurement with the NGS Gravity Program added 25%-35% to the current value of orthometric heights for the inland waterway system they would be worth $24.4-$63.9 million per year. This includes all inland waterway transportation regardless of the type or entity by which it is managed.

[116] National Waterways Foundation, *Inland Navigation in the United States*, Prepared by the University of Kentucky and the University of Tennessee, November 2014 http://www.nationalwaterwaysfoundation.org/documents/INLANDNAVIGATIONINTHEUSDECEMBER2014.pdf

Direct and Indirect Benefit Estimates

Summary of Direct Economic Benefits

Potential direct economic benefits which are shown in this section will be used in scenarios that indicate possible evolutions of actual benefits over time. Potential benefits are annual benefits with 100% adoption. Direct benefits do not include economic multiplier effects and do not include non-economic benefits. Annual benefits were estimated according to two methods which do not duplicate each other.

> **Method 1** is based on experience with the use of geoids in advance of the final geoids for the Gravity Program, applied to the estimate of geospatial spending, plus an allowance for further impacts on infrastructure costs.
>
> **Method 2** derives as the sum of benefits of DEMs and two other applications

Method 1 also shows three components that include only some of the applications covered and are not totaled. They include updates of estimates for long line leveling and the FEMA National Flood Insurance Program that were considered in the 2009 study of CORS and GRAV-D and provide an approximate update on results of a study of the value of NWS river and flood forecasts. Many other applications are implicitly incorporated in the overall estimate.

The components of Method 2 *do* make up its total and provide an indication of the combined value of applications for which estimates could be made. Unduplicated estimates are provided for DEMs, agriculture and marine transportation.

Method 1 produces an estimate of potential direct economic benefits of the NGS Gravity Program based on the 2019 economy of $2.55-$6.05 billion per year (Table 16). Method 2 results in an estimate of potential direct economic benefits of $1.72-$3.23 billion per year. Method 1 is preferred because it is much more comprehensive.

Table 16. Summary of Potential Direct Annual Economic Benefits of the NGS Gravity Program to the U.S. at 100% Adoption Based on the 2019 Economy

Sector or Application	Annual Benefit	Basis	Comments
Method 1. Geospatial Activities Total	**$2.55-$6.05 billion**	Experience with the use of geoids applied to geospatial spending, which was estimated based on occupation data, plus an allowance for other impacts on project end costs and lives	Preferred over Method 2 because it is much more comprehensive.
Long line leveling	$65.0-$97.5 million	The amount of long line leveling is assumed to be half as great as in the 2009 study	The amount is less because of costs and use of available geoids
FEMA NFIP floodplain management	$110-$185 million	Includes $3-$6 million in savings for elevation mapping and $50-$120 million from use of the maps	Allows for insurance becoming voluntary and more costly for structures with greater vulnerability
Benefits through NWS river and flood forecasts	$360-$804 million	Assumed percentage contribution to values from update of National Hydrologic Warning Council study	Includes reservoir optimization, snow melt and other long term flood events, short term forecasts that allowed time for responses and use in the AHPC
Method 2. Sum of Components Total	**$1.72-$3.23 billion**	Sum of estimate for DEMs, agriculture and marine transportation	
Improved Digital Elevation Maps based on Dewberry (2012)	$979 million-$1.469 billion	Based on a percentage of benefits of various enhancements to Digital Elevation Maps	The estimate based on the 2012 Dewberry study is relied on over the 1998 study because the data is more current and complete. The estimate uses the lower value.
Addendum: Updated total of 5 applications from 1998 study	*$400-$800 million*	*Cost reduction from use of high accuracy Digital Elevation Models from the 1998 National Height Modernization Study, updated by change in nominal GDP*	*Includes a range of activities of USACE, FEMA, NWS and several other federal agencies along with local planning and stormwater management efforts*
Agriculture	$700 million-$1.65 billion	Estimated at half of the updated value of GPS for precision farming. Excludes benefit for DEMs which are counted separately.	The estimate does not include use of techniques besides auto-guidance or crops other than grains.
Marine transportation – total			
The PORTS® Program	$16.9-$47.0 million	Based on hypothetical extension of the program to 175 ports	Reflects the preponderance of benefits in the 2016 study of the PORTS® program coming from greater cargo carriage with increased hull clearance
Inland waterways	$24.4-$63.9 million	Illustrative indication of possible order of magnitude	Based on National Waterways Foundation abandonment scenario

Uncertainty in the Economic Benefit Estimates

Ranges were used to reflect uncertainty in some estimates. In some cases, ranges were based on the results of studies, while in others they are based on expert opinion or are suggestive of possible variation in benefits.[117,118] Uncertainty also is represented by scenarios and by the use of alternative discount rates in discounting future benefits.

Economic Multiplier Effects

Direct multiplier effects come about because there is additional spending on sectors that supply equipment, data, software and services. Indirect and induced multiplier effects result when employees gain additional hours, more employees are hired, and/or skill levels increase so spending on consumer goods and services increases. Multiplier effects also can come as a result of increases in activity of business and government sectors using the services when the services advance their capabilities.

Many studies have used multipliers of 2 and sometimes even much larger values.[119] To be conservative a multiplier of 1.4 is used here.

Applying the multiplier to potential economic benefits of $2.55-$6.05 billion per year based on 2018 with Method 1 yields full potential economic benefits of $3.57-$8.47 billion per year at 100% adoption, with a midpoint of $6.0 billion.

> Applying the multiplier to the potential economic benefits of $2.55-$6.05 billion per year with Method 1 yields full potential economic benefits of $3.57-$8.47 billion per year, with a midpoint of $6.0 billion.
>
> With the estimate of $1.72-$3.23 billion for Method 2, the multiplied range is $2.41-$4.52 billion per year, with a midpoint of 3.3 billion per year.

With the estimate of $1.72-$3.23 billion for Method 2, the multiplied range is $2.41-$4.52 billion per year, with a midpoint of 3.3 billion per year.

The economic benefit estimates do not include possible reduced damage from floods and storms with better height information. While they include cost savings in geospatial activities and reduced project cost and increased longevity, they do not include economic contributions of infrastructure projects in excess of their cost.

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[117] NGS computes a variance for blocks assessed in the GRAV-D program that have had perpendicular flyovers. However, NGS does not compute a variance for the combined data and does not currently have the ability to determine it.

[118] If the estimates are unbiased, errors will tend to average out – so it is not appropriate for benefit totals across applications to have ranges that ass the width of the individual ranges. Rather, a typical range can be applied to a point estimate of a total. However, the typical range may have to reflect the possibility that larger categories have different ranges that smaller ones.

[119] For a discussion of some methods see Irving Leveson, *GPS Civilian Economic Value to the U.S., Interim Report*, prepared for the National Executive Committee for Space-Based Positioning, Navigation and Timing, August 31, 2015, pp.9-10 http://www.performance.noaa.gov/wp-content/uploads/2015-08-31-Phase-1-Report-on-GPS-Economic-Value.pdf

Economic Benefit Scenarios

Considerations in Developing the Scenarios

Influences on the Phase-In of Benefits

While the 2022 improvements will simplify the process of obtaining precise orthometric heights by making benchmarking no longer necessary and providing access through CORS and a single point of entry through OPUS Projects, users will have to adapt their methods, and many will need additional training to understand and apply the guidelines and tools. Responses will be mixed. Relatively rapid adoption could take place among organizations and individuals that require high accuracy in commercial and scientific applications and have the necessary professional skills and resources. Baumann notes: "This includes engineering and surveying firms: the transportation, utility, aviation, agriculture, and construction industries; and those agencies monitoring weather forecasts and climate change."[120] However, for some high accuracy users, substantial reprocessing of previous data will be required for comparability over time.

It is not encouraging that 28% of visitors to the NGS Web site during 2016-2018, a group that is probably more sophisticated than average users of NGS services, were not at all aware that NGS will replace NAVD 88 with new geometric and geopotential datum (Figure 3). One expert interviewed for this study thought that even large engineering firms would take ten years to make the transition to the new system.

Most federal agencies are required to use the NSRS, and many of them could adopt the new system in its first few years. Others such as the National Flood Insurance Program will have to wait for map updates to phase in over several years. It also will take considerable time for state laws to change to allow the use of the new reference frames for surveying and mapping.

In the Great Lakes, the last update to the datum was in 1985 and the next is expected in 2025. While the geoid will address surface water levels based on tide gauges, some of the benefits to navigation will await subsequent updating of hydrographic surveys which examine the bottoms of the lakes. Also, nautical charts will be adjusted if heights change by more than one foot. Charts were not adjusted after the 1985 update.

The need for historical comparability will create a long drag on willingness to update requirements and methods.

Counties and cities have largely been ignoring replacing bench marks. However, many will continue to rely on them for a long time because laws and contract requirements often will not be updated quickly and some projects with earlier requirements will go on for some time. The need for historical comparability will create a long drag on willingness to update requirements and methods.

[120] Jim, Baumann, "Moving from Static Spatial Reference Systems in 2022," *esri arcuser*, Winter 2019, p.36 https://www.esri.com/about/newsroom/wp-content/uploads/2019/01/Moving-Static-Spatial-Reference-Systems-2022.pdf

At present, commercial providers of software and services incorporate geoid models that, while internally consistent, are not fully consistent with the NSRS. NGS has been working with commercial vendors through Industry Days and individual contacts. In 2022 when the NGS datum and systems are scheduled to become available, private vendors are expected to incorporate the NGS data and geoid models into their software and be consistent with the NSRS, providing one of the ways the NSRS is accessed. Users can then take the geoid model in the field with RTK. Later on, some vendors may incorporate NGS systems and make it unnecessary for users to access the NGS Website.[121]

> The last experience with introduction of a new datum and the need for upgrades in skills suggest that it will take decades for the new system to be adopted widely after the program is launched.… However, some of those likely to produce the largest benefits could take advantage of the capabilities relatively quickly,…

The last experience with the introduction of a new datum and the need for upgrades in skills suggest that it will take decades for the new system to be adopted widely after the program is launched. Time-dependent parameters are new and will need to be understood. However, some of those likely to produce the largest benefits could take advantage of the capabilities relatively quickly, which could front load the growth of benefits. Assumptions made for alternative paces of adoption in the scenarios reflect the differing considerations.

Natural Disasters, Technology and Other Considerations

The sustainability of the benefits of the program also will depend on the extent to which changes such as earthquakes, volcanoes, subsidence and sea level rise cause differences in heights from the geoid that is published.[122,123] While the GeMS program will provide updates in a few years, the Gravity Program as a whole is not expected to be systematically updated for a long time. Yet, geoid accuracy can hold for decades. While deterioration in accuracy of the geoid would reduce the value of benefits at future dates, large natural changes are expected to generally come beyond the ten year time frame of the benefit calculations and any that do occur are likely to impact limited locations.[124,125]

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[121] This will speed the process of adoption. One expert suggested that most surveyors will probably make use of the new system within five years. However, another emphasizes that most surveyors don't know what they don't know.

[122] Dru Smith, "Temporal Changes to the Geoid and Vertical Datum," NOAA Airborne Gravimetry for Geodesy Summer School, May 27, 2016 https://www.ngs.noaa.gov/GRAV-D/2016SummerSchool/presentations/day-5/1DruSmith_TempGeoid.pdf

[123] Thomas Jacob, *et. al.* judge that local adjustments will be needed once every ten years but extreme events could come sooner. See Derek van Westrum, "An Introduction to Geoid Slope Validation Surveys – What They Are, and Why They Matter," NGS Webinar, July 12, 2018, slide 43 https://geodesy.noaa.gov/web/science_edu/webinar_series/gsvs-introduction.shtml

[124] Thomas Jacob, *et. al*. as reported in Derek van Westrum, "An Introduction to Geoid Slope Validation Surveys – What They Are, and Why They Matter," NGS Webinar, July 12, 2018, slide 43 https://geodesy.noaa.gov/web/science_edu/webinar_series/gsvs-introduction.shtml

[125] Based on analysis of GRACE satellite data, Van de Wal, *et. al*. found that: "The largest geoid rate uncertainty is estimated in the Great Lakes and south-west of Hudson Bay (over 0.3 mm/year) due to uncertainty in continental water storage." Wouter Van de Wal, *et. al*., "Secular Geoid Rate from GRACE for Vertica; Datum Modernization," researchgate.net, January 2010 https://www.researchgate.net/publication/251113071_Secular_Geoid_Rate_from_GRACE_for_Vertical_Datum_Modernization

Changes that could make a difference during the time frame of the benefit scenarios, if they occurred, include:

- An increase in the frequency of extreme weather that increased the value of information to anticipate and address the consequences of severe storms
- A cataclysmic event or magnitude nine earthquake in which one tectonic plate slides under another
- New information, such as a Canadian gravity survey of the Canadian Rocky Mountains (since gravity leaves its signal over long distances)

These are not considered in the scenarios because of the absence of knowledge about whether, when and with what impact they might occur.

The phase in of GPS III satellites and the new ground control system which will start no earlier than 2023 "…will offer triple the accuracy and eight times the anti-jamming capabilities of the satellites currently comprising the U.S Air Force's GPS constellation."[126] Improvements in satellites and systems of other nations can add to accuracy and reliability of GNSS signals as well. However, it has been suggested that the use of multiple GNSS constellations (referred to as multi-GNSS) which includes Europe's Galileo, Russia's GLONASS and China's BeiDou along with GPS), by itself, is not likely to lead to greater accuracy of orthometric heights in the future because each of the constellations has its own biases.

Deflection of the vertical is not expected to be widely used in civilian applications, according to experts at NGS.

The most likely new technology to make a difference in the future is chronometric atomic clocks. Wired together, the clocks would provide relative heights by measuring the distance to other atomic clocks in the fixed positions at which the clocks are located. However, they are currently large, expensive laboratory instruments and their evolution for use in the field is not expected to occur during the ten-year time frame of this study.

Some of the benefits anticipated from the Gravity Program could instead result from efforts of the private sector if the market for precise point positioning (PPP) satellite services was to become large.[127] It is not at all clear whether, how much or how soon that could occur since it would involve costs to users and would not fully compensate for lack of use of related NGS services. PPP is not taken to have a significant effect on the value of future benefits from the Gravity Program in the ten-year scenarios.

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[126] For an overview, see Alan Cameron, "That Was Then. This Is Now," gpsworld.com, March 2019 https://editions.mydigitalpublication.com/publication/?i=572825#{%22issue_id%22:572825,%22page%22:18} For more complete information see www.gps.gov

[127] PPP uses a mathematical model for obtaining greater GNSS accuracy from information on the orbits of the satellites and the behavior of their atomic clocks based on broadcast correction data and local computations. There are a number of variations and combinations with other methods. Use of the technique eliminates the need for a directly accessed based station. However, it can involve subscription costs.

Improvements in applications of Gravity Program data and evolution of new applications for the program over time are not explicitly included in the scenarios and would work counter to biases from exclusion of alternative technologies or other factors.

It is assumed that population and economic activity will no longer grow faster in coastal vulnerable areas than in the rest of the country because of concerns about extreme storms and flooding. Consequently, the overall rate of growth in GDP (which incorporates both population and income) for the nation is used in the benefit scenarios. Growth projections are based on those of the Congressional Budget Office.[128]

Description of the Scenarios

Economic benefits are illustrated in alternative scenarios over 10 years from 2023-2032 based on 2019 price levels and future levels of GDP. A scenario consists of the path with a particular emphasis by which a percentage of potential adoption is reached. Economic multiplier effects are included. Scenarios represent dollar values of benefits above what would be expected in the absence of the NGS Gravity Program.

The three scenarios reach 50%, 60%, and 62% of potential adoption in 2023. Percentage adoption refers to the percent of the value of benefits and not to the percentage of people using the system. It is assumed that the Gravity Program will be operational close to the end of calendar year 2022 so benefits start in 2023. As requested, the scenarios do not go out further than 2023 because there is too much uncertainty about the development of complementary and alternative technologies and other factors. Present discounted values are compared among benefit streams.

The three main scenarios: “baseline,” “fast out of the gate,” and “continuing rapid buildup” are described below.

Baseline. Adoption takes place gradually as upgraded skills and applications are phased in and as the need for legislation and historical comparability constrain adoption. Adoption reaches 25% in the 6th year and 50% in the 10th year.

Fast out of the gate. High value projects and more skilled users adopt the new methods relatively rapidly. This is facilitated by efforts to take advantage of the years until the new vertical datum is deployed. Adoption as a percent of program benefits reaches 35% in the 6th year and 62% in the 10th year.

Continuing rapid buildup in use. Recognition of benefits of the program builds over time and skills develop to take advantage of it. Incorporation of the new geoids by equipment and software providers accelerates adoption but resulting benefits are tempered by some inappropriate “push button” use. Adoption reaches 30% in the 6th year and 60% in the 10th year.

Two other possibilities are noted but not estimated:

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[128] Congressional Budget Office, *The Budget and Economic Outlook: 1919-1929*, January 2019 https://www.cbo.gov/system/files?file=2019-03/54918-Outlook-3.pdf

Delayed Surge. Increased use could be encouraged by a large national infrastructure spending program to support the economy and reduce risks of damage from climate change, but such a program could come with a long lag and might only come with a recession that tempers or negates the benefits that could come with additional adoption. It also could come in the early years of the new geopotential datum when adoption has not ramped up very far. An estimate is not made for this scenario since its likelihood and timing is uncertain.

Delayed Start. In this scenario the complexity of the Gravity Program effort, technical difficulties and/or shortages of skilled staff in NGS result in the program starting in 2023. This variation of the other scenarios would be calculated by shifting the streams of benefits back one year but still including 10 years of use. The effects on the present discounted values of benefits would be small.

The Quantitative Scenarios

The year-by-year benefits under each of the two methods for their middle, low and high levels are shown in Tables 17 and 18. The scenarios are in year 2019 purchasing power and future levels of output based on Congressional Budget Office Projections.

Table 17. Method 1 Scenarios for Annual Economic Benefits of the Gravity Program
(billions of 2019 dollars)

	Scenarios and the Ranges of Their Estimates								
	Lower			Middle			Upper		
Year	Baseline	Fast Out of the Gate	Continuing Rapid Buildup	Baseline	Fast Out of the Gate	Continuing Rapid Buildup	Baseline	Fast Out of the Gate	Continuing Rapid Buildup
2020	0	0	0	0	0	0	0	0	0
2021	0	0	0	0	0	0	0	0	0
2022	0	0	0	0	0	0	0	0	0
2023	0.09	0.15	0.12	0.19	0.32	0.26	0.29	0.49	0.39
2024	0.22	0.34	0.28	0.46	0.72	0.59	0.70	1.10	0.90
2025	0.35	0.54	0.51	0.73	1.13	1.07	1.12	1.73	1.63
2026	0.49	0.74	0.71	1.02	1.56	1.49	1.55	2.38	2.27
2027	0.66	0.96	0.92	1.38	2.00	1.93	2.10	3.05	2.95
2028	0.87	0.87	0.87	1.76	2.46	2.11	2.68	3.75	3.21
2029	1.06	1.43	1.30	2.22	3.01	2.72	3.38	4.58	4.14
2030	1.28	1.67	1.57	2.65	3.51	3.29	4.04	5.34	5.02
2031	1.53	1.95	1.84	3.21	4.08	3.86	4.89	6.22	5.88
2032	1.77	2.19	2.12	3.71	4.60	4.45	5.65	7.01	6.78

Note: Includes multiplier effects.

Table 18. Method 2 Scenarios for Annual Economic Benefits of the Gravity Program
(billions of 2019 dollars)

	Scenarios and the Ranges of Their Estimates								
	Lower			Middle			Upper		
Year	Baseline	Fast Out of the Gate	Continuing Rapid Buildup	Baseline	Fast Out of the Gate	Continuing Rapid Buildup	Baseline	Fast Out of the Gate	Continuing Rapid Buildup
2020	0	0	0	0	0	0	0	0	0
2021	0	0	0	0	0	0	0	0	0
2022	0	0	0	0	0	0	0	0	0
2023	0.06	0.09	0.07	0.08	0.13	0.11	0.10	0.17	0.14
2024	0.13	0.21	0.17	0.19	0.30	0.24	0.25	0.39	0.32
2025	0.21	0.32	0.31	0.30	0.47	0.44	0.39	0.61	0.57
2026	0.29	0.45	0.43	0.42	0.64	0.61	0.55	0.84	0.80
2027	0.39	0.57	0.55	0.57	0.82	0.80	0.74	1.08	1.04
2028	0.70	0.98	0.84	1.01	1.42	1.21	1.32	1.85	1.59
2029	0.63	0.86	0.78	0.91	1.24	1.12	1.19	1.61	1.46
2030	0.08	1.00	0.94	1.09	1.44	1.35	1.42	1.88	1.77
2031	0.92	1.17	1.10	1.32	1.68	1.59	1.72	2.19	2.07
2032	1.48	1.84	1.78	2.14	2.65	2.56	2.79	3.46	3.34

Note: Includes multiplier effects.

Present Discounted Values of Future Benefits

Future values of benefits were discounted to the start of 2023. Discounting can be interpreted as reflecting preferences for a dollar today over receipt of that dollar later, as the cost of borrowing funds or as returns on alternative investments. The discount rate is analogous to the return on investments *above* inflation. Discounted benefits are in 2019 dollars. The 7% discount rate that was promulgated by OMB decades ago is used for the main calculations of present values of future benefits. Since this rate above inflation is much higher than the current “real rate of return” on long term bonds and the real rate expected in the next decade, implications of 3% and 5% discount rates are also shown.

The present discounted value (PDV) of benefits with a 7% discount rate is $8.71 billion under the middle baseline scenario with Method 1 – which is preferred to Method 2 because it is much more comprehensive. Benefits range up to $16.8 billion with faster adoption with a 7% discount rate.

The present discounted value (PDV) of benefits with a 7% discount rate is $8.71 billion under the middle baseline scenario with Method 1 – which is preferred to Method 2 because it is much more comprehensive.

With Method 2, the middle baseline scenario PDV at 7% is $3.99 billion.

Use of alternative discount rates would result in much larger discounted benefit values, on the order of 20% higher with a 5% discount rate compared with a 7% rate and 50% higher with a 3% discount rate (Table 19).

Table 19. Present Discounted Values of Gravity Program Benefits for Alternative Scenarios and Discount Rates
(billions of 2019 dollars)

	Scenarios and The Ranges of Their Estimates								
	Lower			Middle			Upper		
	Baseline	Fast Out of the Gate	Continuing Rapid Buildup	Baseline	Fast Out of the Gate	Continuing Rapid Buildup	Baseline	Fast Out of the Gate	Continuing Rapid Buildup
Method 1									
PDV 3%	6.14	8.05	7.59	12.79	17.36	16.14	19.48	26.45	24.58
PDV 5%	5.05	6.64	6.26	10.52	14.34	13.31	16.03	21.84	20.28
PDV 7%	4.18	5.51	5.19	8.71	11.91	11.04	13.27	18.14	16.82
Method 2									
PDV 3%	3.61	5.53	5.14	5.90	7.96	7.40	7.69	10.39	9.66
PDV 5%	2.96	4.56	4.23	4.84	6.56	6.08	6.31	8.56	7.94
PDV 7%	2.45	3.77	3.50	3.99	5.43	5.03	5.21	7.09	6.57

Note: Includes multiplier effects.

The ranges around all of these numbers are wide, reflecting uncertainty and limited information.

Impact on Jobs

The NGS Gravity Program can result in either increases or decreases in jobs. The first-order effect of cost savings or productivity increases can be a reduction in jobs. The lower cost also may increase demand for products or activities that use the services and result in the addition of jobs. For surveying and associated activities, the expansion of demand due to lower cost may be small since requirements of projects that use the services may be fixed. Increased capabilities may lead to creation of new applications which can result in job expansion. The net effect of all of the changes on payroll could be positive or negative, but with more of the jobs outside geospatial industries. Net effects of cost changes and production and market developments are too conjectural to quantify.

Non-Economic Benefits

The NGS Gravity Program can have large benefits in reduced fatalities and injuries through improved advisories for water-related and other events. In 2018 alone there were 164 fatalities from flash and river floods, coastal storms, rip currents, tropical storms and hurricanes. Environmental benefits can be substantial because of the large numbers of people and activities which are affected. Two cases of reduced fatalities and injuries based on available studies are estimated in Appendix E.

Much environmental information required to analyze benefits of the Gravity Program is fragmented and location-specific, so it is not readily generalizable to the nation. Utilizing it may require specialized technical expertise and extensive analyses.

Suggestions for Monitoring, Data Collection and Research

The estimates of benefits of the Gravity Program in this report are very preliminary because they are made without the opportunity to observe the program in actual operation. Studies of the program in operation would be appropriate when that becomes possible. It also would be useful to have a socio-economic study of forthcoming NGS improvements in the NSRS overall, building on present efforts. In the meantime, more can be done to anticipate how the Gravity Program will meet critical needs and to further its impact.

Several government agencies previously collaborated to produce an analysis of the effects of modernizing the national datums for floodplain mapping in a 2011 report to demonstrate how an improved datum could be used.[129] A new version for floodplain mapping is underway led by NASA. Similar studies for other applications would be useful. It would be beneficial if potential socioeconomic impacts were examined within or in conjunction with such efforts.

Changes in weather and climate pose challenges in making full use of orthometric heights. The record U.S. Rainfall in 2019 with flooding in the Midwest in the Spring and Summer of 2019 and some recent hurricanes exemplify the challenges. Will some ways of using the data become more important or will new ways come to the fore? How will that affect the benefits of updates of the data or the nature of NGS' role in helping constituents understand and effectively use it. More exploration of these themes would be useful.

NGS continually makes extensive efforts at outreach to user communities through technical reports, conferences, Webinars, newsletters, developing the Regional Geodetic Coordinator program, encouraging appropriate curriculum in schools, developing model state legislation, and other means. However, there is still a large unmet need for understanding of the Gravity Program and the new datums. Additional means of outreach might be considered, including:

- Capability for a consolidated online search of materials on the NGS Web site by topic which is independent of the type of material (report, article, Webinar, etc.) and also includes search by date in addition to the current search capabilities, to make the vast amount of material more accessible.

- More writing for less sophisticated professional audiences to encourage upgrading of skills and help provide a knowledge base from which upgrading can advance. An example is a more easily readable public version is part of the Goals of a Geoid Monitoring Service (GeMS) report which is in development. It is recognized that NGS will be better able to do this when it is further along with developing technical explanations for the new NSRS and that much of the broader material will come from academic sources, the private sector and user organizations. NGS also can see if there are opportunities to work more systematically with textbook authors and publishers to encourage the development of widely understandable and up-to-date resources.

- Working with the U.S. Bureau of Labor Statistics to assure that their descriptions of jobs and projections of employment and job openings accurately reflect expected increases in demand

[129] Youngman, Monica, *et*. *al*., *The Effect of Modernizing the National Datums on Floodplain Mapping*, National Oceanic and Atmospheric Administration, National Research Council, November 17, 2011 https://www.ngs.noaa.gov/PUBS_LIB/Floodplain_Pilot_Project_Final.pdf

> and skill levels. Improved information will more accurately signal to counsellors, potential students and job seekers what the opportunities are that they might prepare for and seek.

It is also recommended that NGS include prominently on its Web site, a single page with a comprehensive set of definitions of frequently used terms in relatively easy to understand language. This would help visitors comprehend terms that may be more technical, less complete or less clear in their use on other parts of the site. The definitions can include links to other pages for more detailed or more technical information.

NGS will have to continue to closely monitor rapidly evolving technologies and applications and their impact on its methods and processes even as it seeks to complete and refine its present efforts. Work on the next set of improvements may have to start well before 2032 since the lead times required to transform or adapt complex processes can be great. NGS fully recognizes this and requires appropriate resources to prepare for future changes.

Large adaptations are required for users to take advantage of the improved orthometric heights and rapidly changing technologies, not only to effectively apply the methods, but also so use of the data will be fully effective. In a 2007 study of survey science in the decade 2007-2017, the U.S. Geological Survey concluded:

> “Rapid advances in the technology of data collection have made it possible for scientists to describe complex systems in multiple dimensions in space and time….Therefore, the challenge now is to synthesize this information with models and decision-support tools that can be used to communicate the consequences of human actions to decision makers and resource managers in a language that crosses disciplinary boundaries.”[130]

The need to effectively transition from measurement to decision-making has never been greater than it is today, and NGS support for use of improved orthometric heights derived from the Gravity Program will help others to take the next steps.

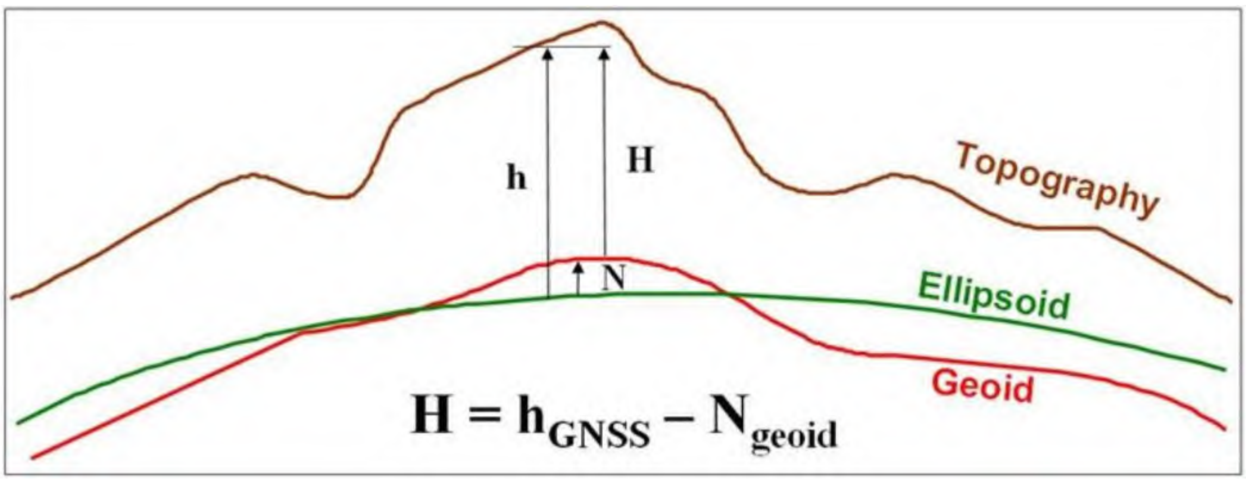
[130] U.S. Geological Survey, *U.S. Geological Survey Science in the Next Decade 2007-2017*, Circular 1309, p.45 https://pubs.usgs.gov/circ/2007/1309/pdf/C1309Text_508.pdf

Appendices

Appendix A. Graphic Depiction of Geodetic Heights

H = Orthometric Height
h = Ellipsoidal Height
N = Geoid Height

Figure A1. Ellipsoid and Geoid Heights



In the continental United States, the geoid is below the ellipsoid, so the value of the geoid height is negative.

For more information, see Daniel R. Roman, "Datums, Heights and Geodesy," slides, National Geodetic Survey, 2007
https://www.ngs.noaa.gov/GEOID/PRESENTATIONS/2007_02_24_CCPS/Roman_A_PLSC2007notes.pdf

Appendix B. Maps of Areas with Significant Uplift or Subsidence

The maps are courtesy of Galen Scott as presented in slide 21-24 of Daniel R. Roman, Steven Hilla, and Kevin Choi, "Modernizing the Geometric Reference Frame," presentation at the NOAA 2017 Geospatial Summit, April 24, 2017 https://geodesy.noaa.gov/geospatial-summit/presentations.shtml

Figure B1

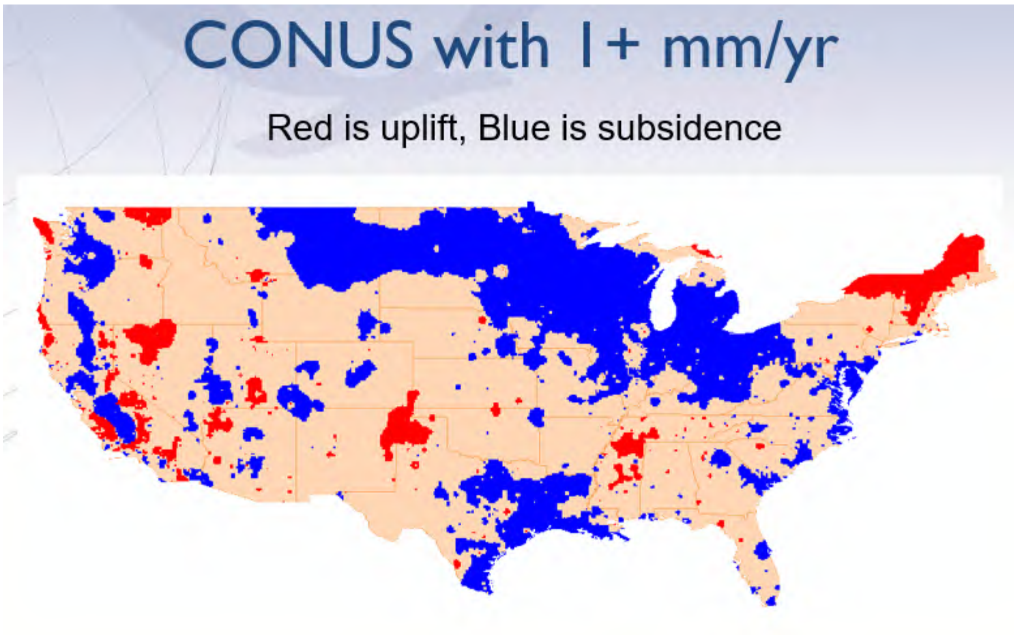


Figure B2

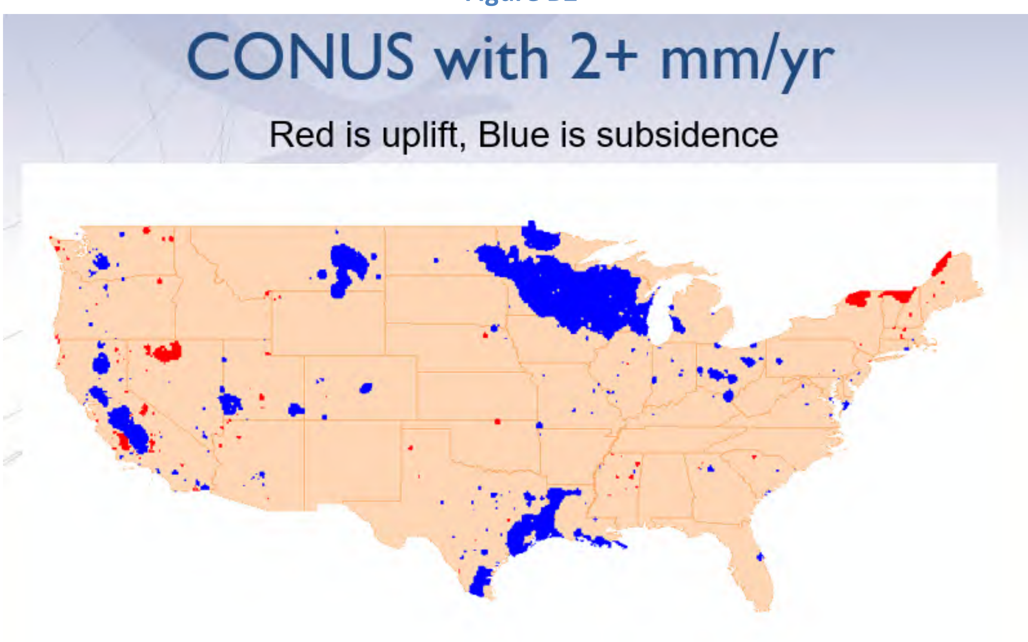


Figure B3

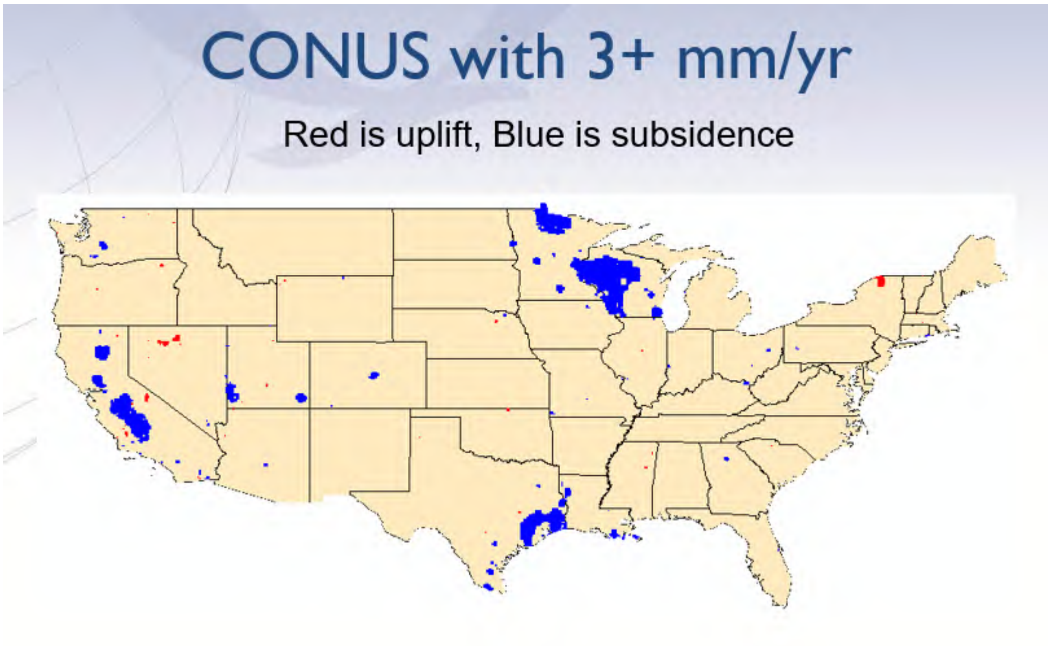
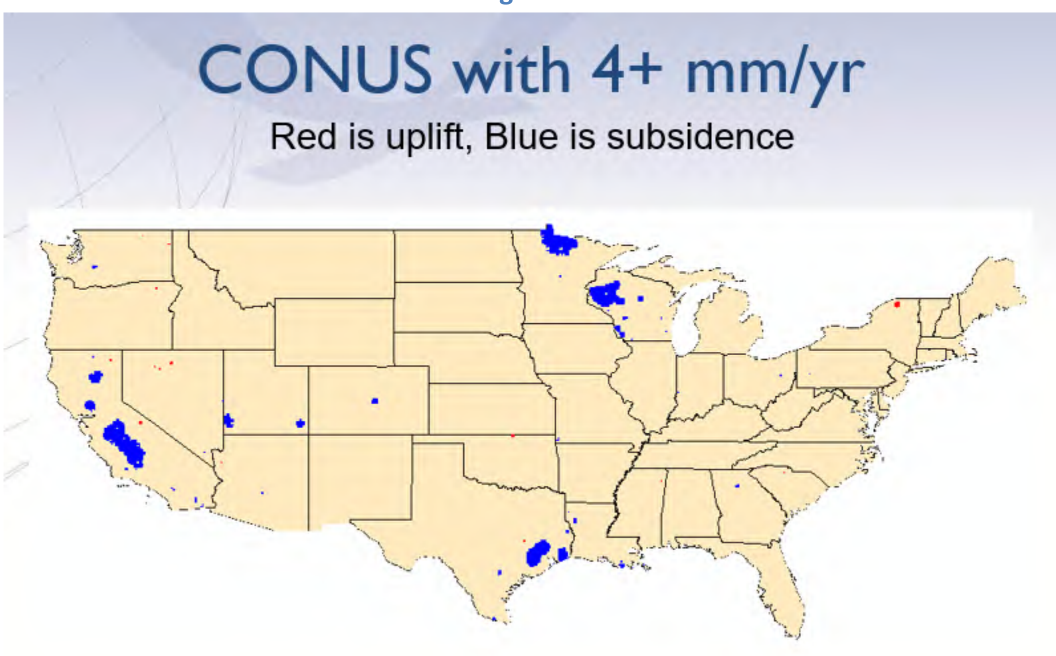
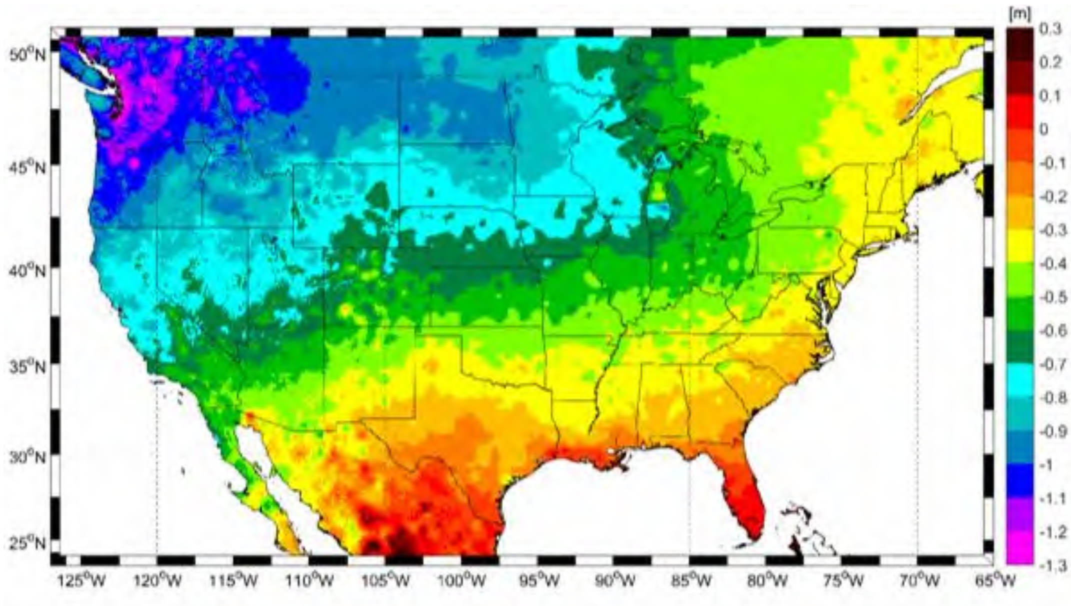


Figure B4



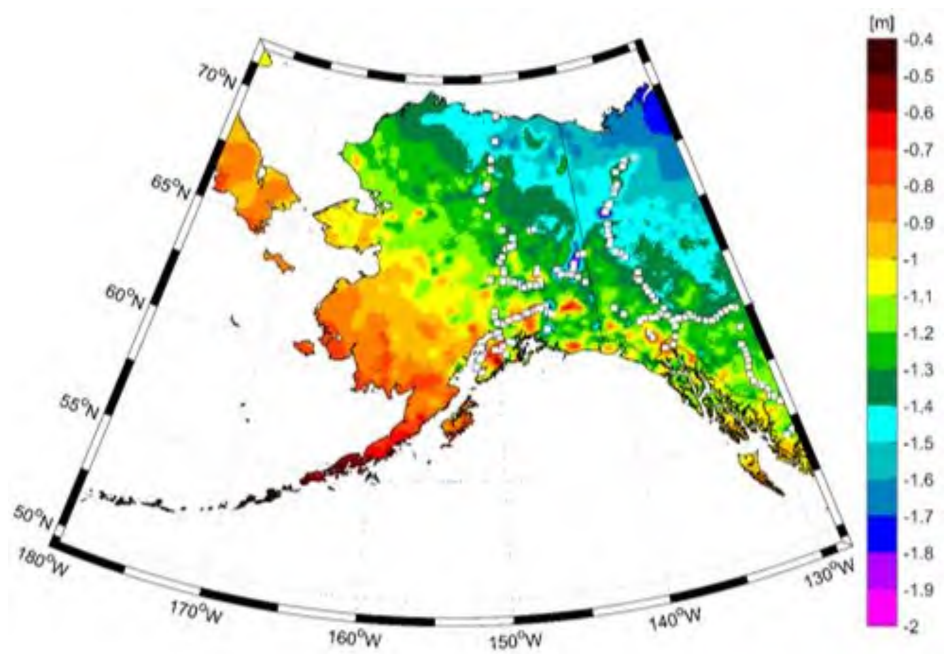
Appendix C. Expected Changes to Orthometric Heights with the Improved Measurement

Figure C1. Expected Changes to Orthometric Heights: CONUS



The continental bias and tilt of the NAVD 88 H=0 surface across CONUS as implied by the latest NGS experimental geoid model based on improved gravity data.

Figure C2. Expected Changes to Orthometric Heights: Alaska



Source: Dru Smith, "Modernizing the National Spatial Reference System," National Geodetic Survey presentation February 6, 2018, slides 20 and 21
https://geodesy.noaa.gov/web/science_edu/presentations_library/

Appendix D. Latin American Geodetic Activities

The reference frame for the Americas is SIRGAS, an acronym for Sistema de Referencia Geocéntrico para las Américas. SIRGAS has adopted ITRF, the International Terrestrial Reference Frame and will include Foundation CORS. They are trying to modify leveling data and plan to integrate with NAPGD2022. This would provide a common system with the U.S. NGS seeks to assist in these efforts.

NGS has been participating in the UN Committee of Experts on Geospatial Information Management: UN-GGIM Subcommittee on Geodesy in support on effort to harmonize geodetic systems among countries. IGLD2025, the forthcoming UN system, will be tied to NAPGD2022. More than 20 countries are working on their own geoid models.

Appendix E. Examples of Reduced Fatalities and Injuries

The numbers of annual fatalities and injuries averted were estimated for two of the applications where it could be based on the studies which were updated (Table E1). If all of the applications expected to be affected by the Gravity Program were included, the benefits would be much larger than the total for these two cases.

Table E1. Some Potential Safety-of-Life Benefits of the NGS Gravity Program to the U.S. at 100% Adoption

Sector or Application	Annual Benefit	Basis	Comments
Method 1. Geospatial Activities Total			
Fatalities and injuries averted through NWS river and flood forecasts:	2.4-5.5 averted fatalities and 0.7-1.6 averted injuries	Based on ratio of damage to fatalities and ratio of damage to injuries during 2013-2017	Value of averted fatalities of $12-$55 million value of averted injuries of $350,000-$1.6 million
Method 2. Sum of Components			
Fatalities and injuries based on the PORTS® Program	0.16-0.36 averted deaths and 0.78-1.76 averted injuries per year	Based on expansion to 175 ports	Value of averted fatalities of $79,000-$360,000 and averted injuries of $378,000-$159 million

Appendix F. NSF Occupation and Economic Sector Data

The National Science Foundation National Center for Science and Engineering provides data on employed U.S. educated scientists and engineers residing in the U.S.. Field of highest degree and employment sector are derived from occasional surveys, the latest of which is for 2013. The National Survey of College Graduates (NSCG) SESTAT data "covers those with a bachelor's degree or higher who either work in or are educated in science or engineering, although some data on individuals who are not scientists or engineers are also included."[131] The NSF surveys are not very granular for occupations, but do contain information on education level, broad type of work activity and salary.

Table F1 shows employment in 2013 in available occupations that may make use of NGS services according to the sector in which respondents worked. In all fields listed the majority worked in business or industry. By far the largest share in the private sector was in the category "science and engineering-related technology and technical fields," which includes many without college degrees. The largest shares in government were in environmental life sciences and civil/architectural engineering.

Table F1. Employment of Scientists and Engineers in Selected Fields, by Employment Sector, NSF, 2013

	Employment Sector				
Field of Highest Degree	**Business/ Industry**	**4-Year College or University**	**Other Educational Institution**	**Government**	**Total**
Agricultural/food sciences	226,000	20,000	17,000	36,000	301,000
Environmental life sciences	91,000	5,000	6,000	56,000	168,000
Earth/atmospheric/ ocean sciences	117,000	19,000	23.000	39,000	199,000
Physics/ astronomy	106,000	45,000	10,000	15,000	176,000
Other physical sciences	21,000	1,000	5	6,000	31,000
Civil/architectural engineering	297,000	14,000	3,000	114,000	428,000
Industrial engineering	164,000	5,000	11,000	11,000	190,000
S&E-related technology and technical fields	383,000	10,000	11,000	18,000	423,000
Source: U.S. National Science Foundation, NCSES Table 7-1 https://www.nsf.gov/statistics/sestat/#sestat-data					

[131] https://www.nsf.gov/statistics/sestat/#sestat-faq

Appendix G. Activities oof USACE, USBR and TVA

Available information is presented on activities and values of benefits for these agencies without attempting to estimate the current value of orthometric heights in their operations or the potential contribution to those activities of improved orthometric heights informed by NGS Gravity Program. That is because of overlap with some of the categories for which estimates were made, the lack of sufficient detail to reconcile methods, and the absence of a clear basis for estimating increases in benefits with the Gravity Program.[132] However, there is no doubt these agencies produce large benefits that are not otherwise counted.

USACE Net National Economic Development Benefit Estimates

The U.S. Army Corps of Engineers (USACE) describes itself as "the nation's lead water resources development agency."[133] The USACE Institute for Water Resources calculates annual benefits of each of its programs based on a concept called National Economic Development (NED) benefits which is defined as changes in the economic value of the national output of goods and services. Net benefits, which is the measure USACE relies on, are net of USACE costs in obtaining those benefits. The averages for FY2012-FY2016 reported by USACE are shown in Table G1. Averages were used because values fluctuate a lot from year-to-year. The estimates do not include multiplier effects.

The basis of the estimates is described in Table G2.[134] The majority of benefits at $54.5 billion in 2016 are for flood risk management. These are based on reduced damage.
Orthometric heights are estimated to contribute significantly to the $24.7 billion of benefits for coastal and inland navigation by reducing damage. Orthometric heights define accumulations of silt to support dredging and locating submerged obstacles, as well as to managing water flow from reservoirs for hydropower and residential and commercial use and contributing to decisions about construction for water management.

Hydropower plants can generate power to the grid immediately, providing power at peak times and essential back-up power during major electricity outages or disruptions. Hydropower facilities produce extensive benefits for flood and drought control, irrigation, water supply, inland navigation, recreation and tourism and environmental management.

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[132] While there are similar difficulties in assessing benefits for inland navigation which is included, the intent is to limit the extent to which the overall benefit estimates depend on less certain judgements.
[133] U.S. Army Corps of Engineers, Institute for Water Resources, *Value to the Nation of the U.S. Army Corps of Engineers Civil Works Program: Estimates of National Economic Development (NED) Benefits and Revenues to the U.S. Treasury for 2010*, 2013-R-09, December 2013, p.2
http://www.iwr.usace.army.mil/Portals/70/docs/iwrreports/2013-R-09_vtn.pdf
[134] Also see U.S. Army Corps of Engineers, Institute for Water Resources, *Value to the Nation of the U.S. Army Corps of Engineers Civil Works Program: Estimates of National Economic Development (NED) Benefits and Revenues to the U.S. Treasury for 2010. op. cit*.

Table G1. Net National Economic Benefits of USACE Programs, FY2012-FY2016 Average	
Program	**Net Benefits** (billions of 2016 dollars)
Flood risk management	54.5
Coastal navigation	11.5
Inland navigation	13.2
Water supply	5.9
Hydropower	2.2
Recreation	1.9
TOTAL	**89.2**
Source: https://fastfacts.corpsresults.us/fastfacts/nationalfastfacts.cfm	

Table G2. Primary NED Benefit Measures for Specific Goods and Services	
Goods and Services	**Primary Benefit Measure**
Flood damage reduction	Reduced property damage
Hurricane and storm damage reduction	Reduced property damage
Transportation – inland & deep draft navigation	Reduced transportation costs
Municipal and industrial water supply	Market value of output, or alternative cost of providing equivalent output when market price does not reflect marginal costs
Hydropower	Market value of output, or alternative cost of providing equivalent output when market price does not reflect marginal costs
Agriculture	Net income from increased crop yields and/or decreased production costs
Commercial fishing	Net income from increased catch and/or decreased production cost
Recreation	Actual or simulated (shadow) prices, or administratively established values for site services
Source: U.S. Army Corps of Engineers, Institute for Water Resources, *National Economic Development Procedures Manual, Overview*, IWR Report 09-R-2, June 2019, Table 4.1 https://www.iwr.usace.army.mil/Portals/70/docs/iwrreports/09-R-02.pdf	

USACE produced 72.341 million MWh of electricity in FY 2014 which was valued at $2.4 billion for their 75 hydropower plants based on sales.

The NED values are typically much greater than benefits estimated from other sources even though they apply only to USACE programs. Moreover, USACE NED benefits are net of costs while other estimates relied on in this study are not. USACE estimates much larger than others not only because of the scale of USACE operations, but also in large part because the focus of USACE is on building infrastructure projects and not just applying information for operations.

The value of USACE facilities and the services derived from them reflects the results of using various datums and methods of measuring orthometric heights over many years.

The estimates for FY2012-FY2016 are updated to 2018 in Table F3 by the 22.1% change in GDP between the periods to account for growth and inflation.

Table G3. Estimated Net National Economic Benefits of USACE Programs, 2018

Program	**Net Benefits** (billions of 2016 dollars)
Flood risk management	66.6
Coastal navigation	14.0
Inland navigation	16.1
Water supply	7.2
Hydropower	2.7
Recreation	2.3
TOTAL	**108.9**
Source: https://fastfacts.corpsresults.us/fastfacts/nationalfastfacts.cfm	

U.S. Bureau of Reclamation Overall Benefits

The Bureau of Reclamation (USBR) maintains 475 dams. USBR is the nation's largest wholesale water supplier, operating 338 reservoirs with a total storage capacity of 140 million acre-feet. It delivers 10 trillion gallons of water to more than 31 million people each year. It provides 1/5 of Western farmers (140,000) with irrigation water for 10 million farmland acres that produce 60% of the nation's vegetables and one quarter of its fresh fruit and nut crops. USBR, with partners, manages 289 recreation sites that have 90 million visits per year.

The Bureau of Reclamation sales value of hydropower, water and recreation was $21.56 billion in FY 2014.[135] This consisted of:

Hydropower $1.21 billion
Irrigation water $15.31 billion
Municipal and industrial water $3.84 billion, and
Recreation $1.21 billion

The U.S. Bureau of Reclamation activities contribute $67 billion to economic output each year and support 458,000 jobs in activities across 17 states (including economic multiplier effects).[136]

The U.S. Department of Interior FY 2016 Economic Report estimates that the irrigation, municipal and industrial water storage and supply and recreation activities of the U.S. Bureau of Reclamation had a direct economic contribution of $18.73 billion.[137]

USBR irrigation water had a direct economic contribution of $13.09 billion.

Municipal and industrial water had a direct economic contribution of $4.23 billion.

Recreation had a direct economic contribution of $1.41 billion.

The U.S. Bureau of Reclamation (USBR) is the second largest producer of hydropower in the United States, operating 53 hydroelectric power plants that produced an average of 40 billion kWh of electricity annually over the last 10 years. 15% of the nation's hydropower is produced by its facilities.[138]

Tennessee Valley Authority Overall Benefits

TVA's 80,000 square mile service region includes 9 million residents and 800 miles of navigable waterways in 7 states. TVA provides flood control and navigation for the Tennessee River system through management of its 29 hydropower dams, 17 non-hydropower dams and reservoirs.

Total water withdrawals during 2010 were estimated to average 11,951 million gallons per day (mgd) for off-stream uses.[139] Water use was primarily for power so an estimate for other uses is not made. TVA uses of water were:

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[135] U.S. Department of Interior, *U.S. Department of Interior Economic Report, FY 2016*, September 25, 2017 https://www.doi.gov/sites/doi.gov/files/uploads/fy_2016_doi_economic_report_2017-09-25.pdf

[136] U.S. Department of Interior, Bureau of Reclamation, *Fact Sheet*, downloaded April 22, 2017 https://www.usbr.gov/main/about/fact.html

[137] U.S. Department of Interior, *U.S. Department of Interior Economic Report, FY 2016*, September 25, 2017 https://www.doi.gov/sites/doi.gov/files/uploads/fy_2016_doi_economic_report_2017-09-25.pdf

[138] U.S. Department of Interior, Bureau of Reclamation, *Fact Sheet*, downloaded April 22, 2017 https://www.usbr.gov/main/about/fact.html

[139] Charles E. Bohac and Amanda K. Bowen, *Water Use in the Tennessee Valley for 2010 and Projected Use in 2015*, TVA, July 2012 https://www.tva.gov/file_source/TVA/Site%20Content/Environment/Environmental%20Stewardship/Water%20Quality/water_usereport.pdf

Thermoelectric - 10,046 million gallons per day (mgd) (84.1 percent of total use)
Industrial - 1,148 mgd (9.6 percent of total use)
Public supply - 723 mgd (6 percent of total use)
Irrigation - 34 mgd (less than 1 percent of total use)

TVA operates 29 power-generating dams throughout the Tennessee River system and a pump-storage plant which together produce 9% of the power in a system that generates electricity from diverse sources. TVA also purchases power from eight dams on the Cumberland River operated by the Army Corps of Engineers. In fiscal year 2016 TVA sold more than 155 billion kilowatt-hours of electricity with revenue generated equal to about $10.5 billion.[140]

Hydropower revenue is 9% of $10.5 billion or $945 million (including pumped storage). If 20% is excluded as the value of purchased power, produced power is valued at $756 million.

[140] https://tva.com and https://tva.gov

Interviews and Discussions

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Abbreviations

3DEP	3D elevation Program
AHPS	Advanced Hydrologic Prediction Service
AHPS	Advanced Hydrologic Prediction Service
BCA	Benefit Cost Analysis
BCG	Boston Consulting Group
BLS	Bureau of Labor Statistics
CO-OPS	Center for Operational Oceanographic Products and Services
CORS	Continuously Operating Reference Stations
DEMs	Digital Elevation Maps
DORIS	Doppler Orbitography and Radio Position Integrated by Satellite
FIG	International Federation of Surveyors
FIM	Flood Inundation Map
GDP	Gross Domestic Product
GeMS	Geoid Monitoring Service
GIS	Geographic Information Systems
GNSS	Global Navigation Satellite Systems
GOES	Geostationary Operational Environmental Satellites
GPS	Global Positioning System
GRAV-D	Gravity for the Redefinition of the American Vertical Datum
GSVS	Geoid Slope Validation Surveys
IEEE	Institute of Electrical and Electronic Engineers
IFSAR	Interferometric Synthetic Aperture Radar
ITS	Intelligent Transportation System
LIDAR	Light Detection and Ranging
mgd	million gallons per day
MODT	Mean Ocean Dynamic Topography
MSST	Mean Sea Surface Topography
NAD83	North American Datum of 1983
NAPGD2022	North American-Pacific Geopotential Datum of 2022
NAVD88	North American Vertical Datum of 1988
NDGPS	Nationwide Differential GPS
NED	National Elevation Database
NED	National Economic Development
NED	National Economic Development
NFIP	National Flood Insurance Program

NGS	National Geodetic Survey
NHWC	National Hydrologic Warning Council
NOS	National Ocean Service
NSCG	National Survey of College Graduates
NSF	National Science Foundation
NSRS	National Spatial Reference System
NWIS	National Water Information System
OPUS	Online Positioning User Service
PDV	present discounted value
PORTS	Physical Oceanographic Real-Time System
PPP	precise point positioning
SDI	Spatial Data Infrastructure
SFHAs	Special Flood Hazard Areas
SLOSH	Sea, Lake and Overland Surges from Hurricanes
TRF	Terrestrial Reference Frame
USACE	U.S. Army Corps of Engineers
USBR	Bureau of Reclamation
USD	US Dollar
USGS	US Geological Survey
VLBI	Very Long Baseline Interferometry
VSL	Value of Statistical Life

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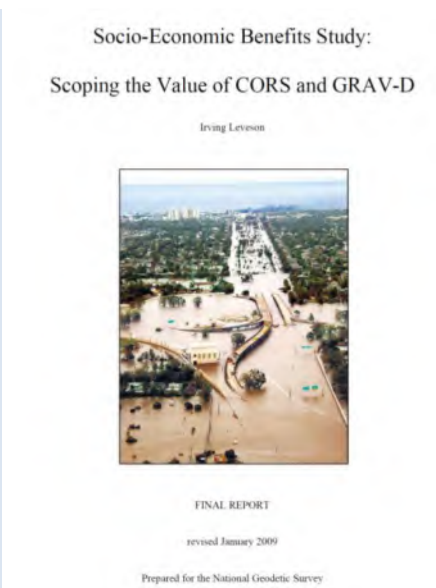
Previous Socio-Economic Studies for NGS

Dr. Leveson previously conducted socio-economic studies of CORS and GRAV-D and for the NGS Coastal Shoreline Mapping Program. He was the principal researcher on the 2017 ARCBridge study of the NGS Regional Geodetic Advisors Program. The reports and descriptions are online at the following locations:



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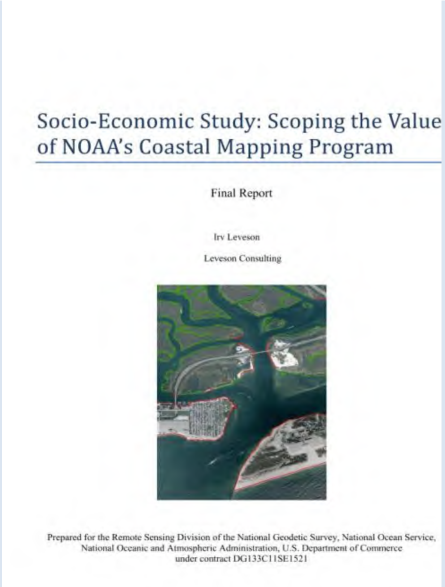
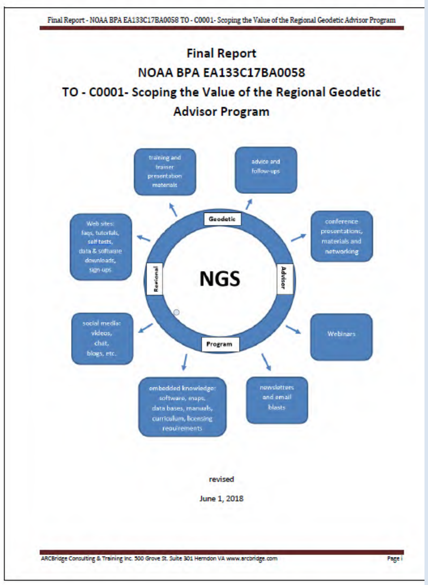


Description available at:
http://www.noaanews.noaa.gov/stories2012/032812_coastalmapping-economicvalue.html
Full study available at:
https://geodesy.noaa.gov/PUBS_LIB/CMP_Socio-Economic_Scoping_Study_Final.pdf



Available at:
https://www.ngs.noaa.gov/PUBS_LIB/reg-geodetic-advisor-prog-socio-economic-scoping-study-6-1-18.pdf

Leveson Bio

Dr. Leveson has strong analytical skills in economics, business and public policy and extensive experience analyzing programs, markets and technologies. His background includes strategic and economic consulting and research in private industry, non-partisan think tanks, and government. Dr. Leveson has consulted for NOAA and affiliates on a wide range of issues for the last 18 years. Current studies for NGS are being performed as a consultant to ARCBridge Consulting and Training, Inc.

Dr. Leveson holds a Ph.D. in economics from Columbia University. Prior to establishing Leveson Consulting in 1990, he served as Senior Vice President and Director of Research of Hudson Strategy Group, Director of Economic Studies of the Hudson Institute, Assistant Administrator for Health

Systems Planning for the New York City Health Services Administration, and as a research director for the New York City Planning Commission. He also was an economist with the RAND Corporation and an analyst with the National Bureau of Economic Research. Dr. Leveson is a member of the Institute of Navigation, the American Meteorological Society, the American Economic Association and the National Association for Business Economics.

His books include *Economic Security*, *American Challenges*, *Western Economies in Transition* (co-ed.), *The Future of the Financial Services Industry* (main author), *Analysis of Urban Health Problems* (co-ed.) and *Quantitative Explorations in Drug Abuse Policy* (contributor and ed.).

His work with NOAA has included support to the Chief Economist over a decade, reports on a wide range of subjects including three previous studies for NGS and providing assistance in applying social science to issues and programs through workshops and educational materials. Recent work has included examining markets, applications and benefits of GPS and assessing applications, and benefits of data from GOES weather satellites along with risks from spectrum interference.