Geodetic Surveying, Earth Modeling, and the New Geodetic Datum of 2022

PDH330

3 Hours

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Geodetic Surveying Final Exam

1. Who established the U.S. Coast and Geodetic Survey?
   A) Thomas Jefferson
   B) Benjamin Franklin
   C) George Washington
   D) Abraham Lincoln

2. Flattening is calculated from what?
   A) Equipotential surface
   B) Geoid
   C) Earth's circumference
   D) The semi major and Semi minor axis

3. A Reference Frame is based off how many dimensions?
   A) two
   B) one
   C) four
   D) three

4. Who published "A Treatise on Fluxions"?
   A) Einstein
   B) MacLaurin
   C) Newton
   D) DaVinci

5. The interior angles of an equilateral planar triangle adds up to how many degrees?
   A) 360
   B) 270
   C) 180
   D) 90

6. What group started xDeflec?
   A) NGS
   B) CGS
   C) DoD
   D) ITRF

7. When will NSRS adopt the new time-based system?
   A) 2022
   B) 2020
   C) Unknown due to delays
   D) 2021

8. Did the State Plane Coordinate System of 1927 have more zones than the State Plane Coordinate System of 1983?
   A) No
   B) Yes
   C) They had the same
   D) The State Plane Coordinate System of 1927 did not have zones

9. A new element to the State Plane Coordinate System of 2022 is:
   A) The addition of Low Distortion Projections
   B) Adjoining tectonic plates
   C) Airborne gravity collection
   D) None of the above

10. The model GRAV-D (Gravity for Redefinition of the American Vertical Datum) created will replace _____________ and constitute the new vertical height system of the United States
   A) Decimal degrees
   B) Minutes
   C) NAVD 88
   D) All of the above

Introduction to Geodetic Surveying

The early curiosity of man has driven itself to learn more about the vastness of our planet and the universe. In earlier times of human development, our understanding of our whereabouts in the world were limited. Over time, we desired to know more and to stretch further than what was in our immediate vicinity. Our world interest grew the more we speculated about our identity, ability and the composition of our surroundings. Advances in science allowed us to determine our exact location on Earth with respect to its shape.

Geodetic Surveying aims to describe and measure the extensive nature and actual shape of the Earth. In order to perform this we must use the accompanying and supportive science of geodesy. “Geodesy is understood as a branch of applied mathematics that determines by observation and measurement the exact positions of points and the figures and areas of large positions of the earth’s surface, the shape and size of the earth and the variations of terrestrial gravity.” (1)

Geodesy is a highly specialized, applied science that uses many basic physical and mathematical components to arrive at the conclusions and understanding it yields. The Department of Defense (DoD) has been a primary influence for the development of modern geodesy for mapping and artillery control purposes as well as satellite tracking, global navigation and defensive missile operations.

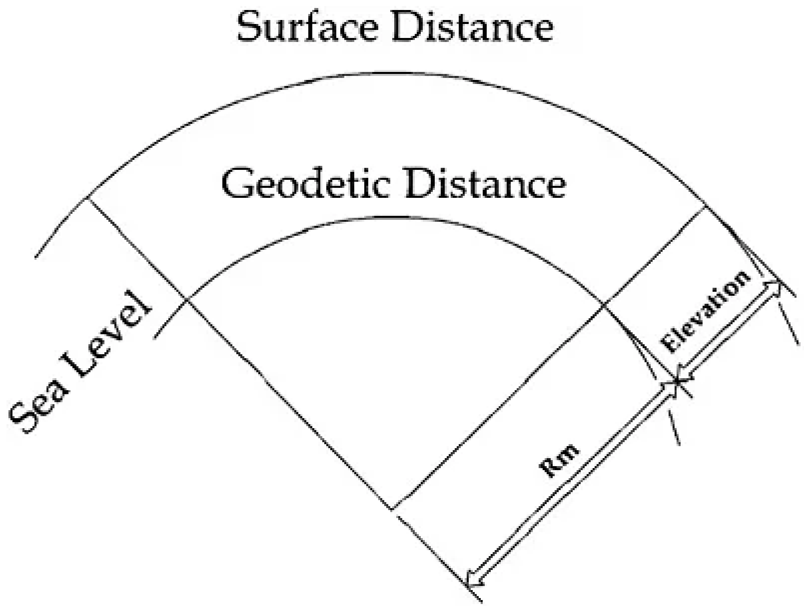
Due to the evolving nature of military environments, geodetic problems have become critical to the armed forces of the world. The development of long and close range weapon systems has created a mandatory requirement to provide detailed cartographic coverage of the regions that are of strategic significance. The need to create geodetic computations between areas with unrelated datum’s has necessitated unification of these areas.

There have been major changes since WWII, but by the 1940’s, the majority of developed nations had their own geodetic systems birthed by both economic and military demands. It was rare for countries, even in close proximity, to use the same geodetic datum. As for the case of international surveys, the only ones that existed for the majority of geodetic history were long arcs used for determining the shape and size of Earth. Obviously, this resulted in a great deal of differing datum’s, surveys and measurements. There was also a major difference in the national maps presented by each country.

With distance requirements increasing for military purposes, the positioning information became less and less useful. The capacity of corresponding weapon systems was able to rise until the scope expanded beyond a nation’s limits. Many countries long understood this, so establishing a single datum (geodetic survey starting point) was the most viable solution. In order to create a single datum for the largest amount of area while adjusting to local systems, existing datum’s had to set forth the initial measurements.

Eventually, the desire for more precise geodetic information grew beyond military needs and into more economic ones. Commerce and trade was vital to a global economy and for the well-being of everyone on earth. This led to further cooperation and pursuit of geodetic surveys to serve the needs of an evolving world.

Geodetic Surveying considers the full dimensionality of the planet. This allows us to determine the most accurate shape possible at any given time, while keeping account of the extensive nature of the Earth. What this means is we will not be able to produce an exact figure but instead create tightly restrained parameters of control to produce and measure survey points to bring us to as close to an exact surface measurement as possible. (2)



(Image 1.1)

We can differentiate geodetic surveying from plane surveying in the simple fact that geodetic surveying accounts for the curvature of the Earth. This allows us to achieve higher precision and extend over larger project areas, while plane surveying is useful when measuring small project areas. Geodetic surveys produce a higher level of accuracy of true ground distances by projection onto the calculated surface by taking into account the latitude, longitude and height of a specific coordinate. Each point has a specific combined factor, but surveyors typically calculate one combined factor for a given project location dependent on the overall area that needs to be surveyed.

We understand geodesy as a science that finds positions on our planet while determining the corresponding gravitational fields. This seems as simple as knowing the shape and supportive mathematical formulas. What is important to note is that a great deal of our technology to date is dependent upon and allowed for because of geodesy and our understanding of the subject.

Navigation, for instance, would be a lost cause and quite chaotic without more recent geodesic developments. Geodesy is vital to geophysics, climatology, astronomy and like-scientific fields. We can only understand components of climate change (i.e. rising sea levels) by way of geodesy and its related technology. Space exploration and our understanding of the vastness beyond our planet is only possible because of this branch of science.

Geodesy is a large and very significant field of study measuring and monitoring the size and shape of the Earth and point locations for over 200 years. Thomas Jefferson established the U.S. Coast and Geodetic Survey, which evolved into the National Geodetic Survey (NGS), in 1807.

The primary reason this was established was to survey the coast of the United States and increase the safety of maritime travel by creating navigational charts.

We can break this subject up into sub domains such as satellite geodesy, physical geodesy, geometrical geodesy as well as other subdivisions. Satellite geodesy gives us the ability to collect data from orbiting satellites for a variety of uses. The launching of Sputnik on October 4th, 1957 was the birth of the space age and positioning on Earth using receivers. The first use of artificial satellites for geodetic positioning was Echo I, which launched May 13th, 1960.

Shortly after, The Coast and Geodetic Survey (C&GS) established a program to determine precise locations on Earth using geometric satellite triangulation. This being the fundamental basis of GPS or Global Positioning Systems.

Geometrical geodesy focuses on the geometrical relationships measured by ways of triangulation, trilateration, electronic surveys and other methods of deducing the size and shape of the Earth and its accompanying positions of the surface area. We must apply the principles of geometry and trigonometry to be able to survey. By taking linear and angular measurements, we are able to determine and delineate the form, extent and position of a particular area or groups of areas and know their true shape and size relative to a coordinate system.

The oldest method of positioning is Astronomic Position Determination. By using astronomic positions with other survey data (triangulation and trilateration), geodesists are able to establish precise positions and locations of places and objects. Astronomic Observations are achieved through theodolites, zenith cameras and prismatic astrolabes.

Triangulation is the most common of all geodetic survey techniques and requires very accurate instruments. In essence, triangulation is comprised of measuring the angles of a series of triangles where all established positions are mathematically related to one another with a bearing and distance.

Trilateration is an additional survey method that relies on radar and aircrafts taking measurements over very large distances. This method determines position from at least three known points.

Traversing is the easiest and least involved way to extend control (primary measurement starting point) and attain further survey measurements. A surveyor must begin with a known position (with azimuth to another point) and measure the angles as well as distances between a series of points in order to extend the survey network and measure beyond the known and established points.

Geometrical geodesy allows us to describe locations and compute points on a given ellipsoid model taking into account the semi-major and semi-minor axis. Meridians and parallels form an orthogonal network of reference curves on the surface. (3)

Physical geodesy is essential for establishing heights (that are the basis of all survey measurements) as well as the gravitational fields of Earth. By way of deduction, this branch uses characteristics and measurements from the Earth's gravitational field (and its supportive/accompanying theories) to know the geoid shape. When combined with arc measurements, the corresponding size of the Earth is determined. Information of the gravitational field on Earth is equally important, as well as, necessary to compute the Earth's flattening, gravimetric deflections and geoid undulations. (1)

Satellite Geodesy was proliferated by various scientific papers in the early 1950's, which advocated for satellites for geodetic purposes. During this time, Project Vanguard (1958-1959) provided data that the Smithsonian Astrophysical Observatory (SOA) outlined for geodetic purposes advocating for Satellite Geodesy. The project yielded a wealth of information and knowledge as well as techniques and theories. This, along with the development of the EDM (Electronic Distance Measuring Device) and data processing equipment led to a consistent growth in space technology. Satellites for geodetic purposes were being developed, launched and used to observe and provide usable spatial data.

Project ANNA was the first actual geodetic satellite to be launched (1962) by the Department of Defense (DoD) and NASA (the National Aeronautics and Space Administration) along with supportive civil agencies. Project ANNA gave way to many observational systems being developed and enhanced. Some examples of these are Doppler, electronic ranging and various geodetic cameras.

The observational systems used for retrieving geodetic information from satellites were optical and electronic. "These systems have made it possible to perform various geodetic measurements to relate known or unknown positions to the Earth's center, to relate unknown positions to existing triangulation networks, and to relate the triangulation networks to each other." (1)

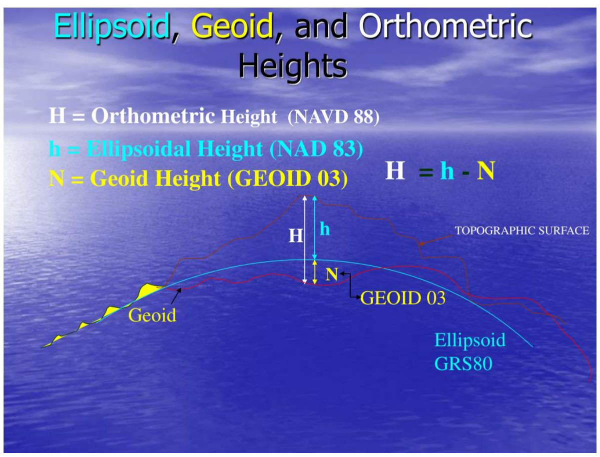
Geodetic positioning with cameras was also possible because of early satellite geodesy. Baker Nunn, MOTS, PC-1000 and BC-4 performed optical tracking and gave photographic observations (flashing light) against the background of accurately determined stars.

SECOR (Sequential Collation of Range) was a system later introduced to ANNA. "The system operated on the principle that an electromagnetic wave propagated through space undergoes a phase shift proportional to the distance traveled." (1) The signal (phase modulated) could be read once it returned to the ground station from the satellite transponder. This phase shift was measured electronically after its round trip and resulted in a range output.

The Doppler observational system stems from the Doppler effect and is used for geodetic purposes. On the premise that when a satellite transmitter puts out a continuous unmodulated wave (at fixed frequency) the signal returned will show a change in frequency caused by relative velocity of both the observation station and the satellite itself. To clarify, we draw from the example of the pitch of soundwaves changing when the sound source approaches and recedes from an observer. In example: a train whistle changes when approaching the train station and conversely when departing. As the train approaches, wavelengths shorten while pitch increases then wavelengths lengthen and pitch decreases as it moves away. It is important to note that Doppler tracking has been the most reliable and useful (mostly because it is passive, data is digital and weather does not affect its readings) out of the many satellite observation systems.

Laser ranging systems and data were also brought into the world geodetic systems by the Smithsonian Astrophysical Observatory (SAO), NASA and the DoD. “The laser has been adapted to measuring distances over the Earth's surface and for computing ranges from Earth stations to satellites and the lunar surface.” (1) A clock activates the laser instrument, pointed at a target, when necessary. The laser reflects back light that is photo electrically detected and measures time of flight (yielding range data) by using special reflectors. In order to receive the reflection of the beam, either a telescope or optical device will be set adjacent to the mounted laser transmitter. For satellite laser ranging, “the interval between the outgoing and returning pulse from the satellite is measured very accurately and then transformed into a range measurement”. (1) The measurement is corrected for atmospheric refraction and even with the Earth’s shadow, as well as daylight hours, laser ranging is still possible.

Let us first take the time to look at some key terms for the purpose of understanding.



(Image 1.2)

Astronomic Position – The position on the Earth’s surface calculated from the measurement of stars in the sky.

Celestial Coordinate System – A coordinate system used to define positions of various stars on the celestial sphere.

Ellipsoid – A reference surface that derives by rotating an ellipse about the minor axis.

Ellipsoidal Height – Also referred to as geodetic height, typically represented by a coordinate pair, this is a point on the ellipsoid measured along a perpendicular line from the ellipsoid to the Earth’s surface.

Flattening – The semi major axis minus the semi minor axis, then divided by the semi major axis written as $f = (a-b)/a$.

Geoid – An equipotential surface that typically represents the global mean sea level, being a close approximation of the Earth’s true shape. (3)

Geiod Undulation – The distance between the geoid and ellipsoid. The geoid undulation is positive when above the ellipsoid and negative when below.

Global Geodetic Reference Frame (GGRF) – “A generic term which describes the framework which allows users to precisely determine and express locations on Earth, as well as, to quantify changes of the Earth in space and time.” (4)

Gradiometry – The change of gravity components in a measurement derived from gradient changes of the gravity vector.

Gravimetry – Relative or absolute measurements involving the total magnitude of the gravity vector over a specific length and time. (5)

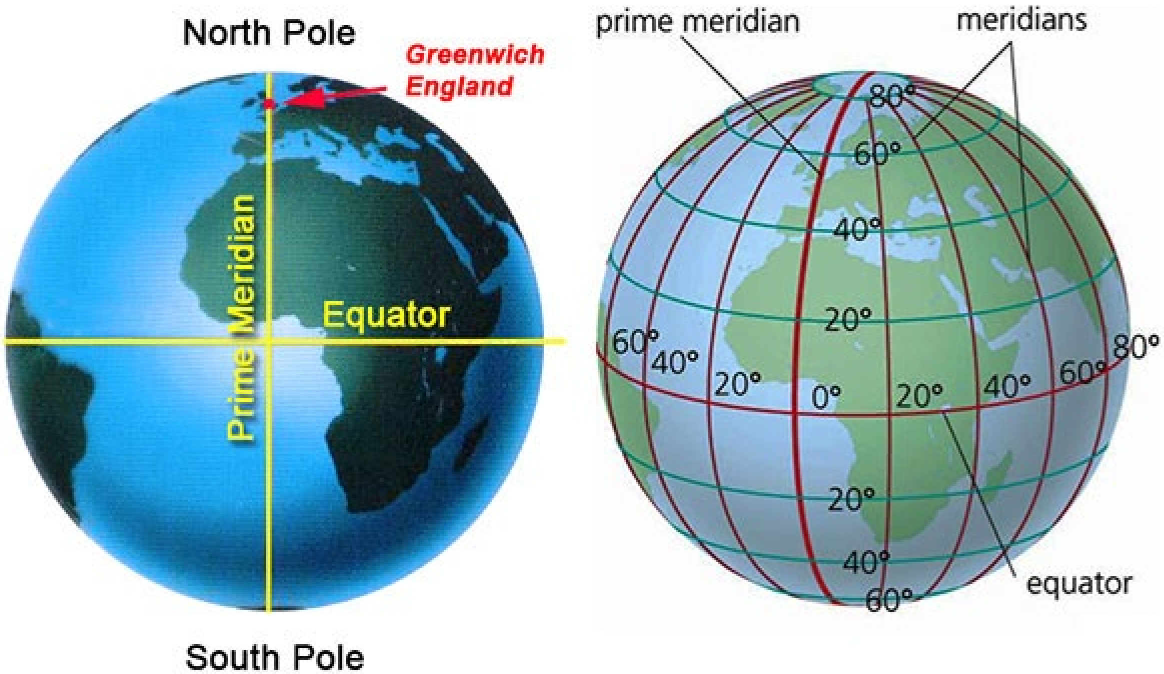
Horizontal Datum – “A specified coordinate system for a collection of positions on the surface of the Earth. Traditionally, horizontal datums have used classical surveying methods (i.e. Measuring distances and angles through triangulation surveys) to best fit to the surface of the Earth.” (6) NAD 83 or the North American Datum of 1983 is the current model used in the United States.

Meridian – A line of longitude, running north south along the surface of the Earth terminating at the North and South Poles. (See Image 1.3)

National Spatial Reference System (NSRS) – A system of mapping throughout the United States that defines latitude/longitude, elevation, scale, orientation and gravity that encompasses all the elements of geodesy.

Orthometric Height – The length between a point and the standard equipotential surface (Geiod) along a plumb line.

Parallel – A line of latitude, running east west along the surface of the Earth parallel to the equator.



(Image 1.3)

Plumb Line – A line that is measured in the direction of gravity.

Reference Ellipsoid – A flattened or oblate spheroid with a semi major and semi minor axis that is a mathematically restrained surface built to approximate the geoid.

Reference Frame – A four-dimensional coordinate system in which three coordinates are spatial dimensions over a given period of time.

Satellite Interferometry – Radio interferometry using satellite signals in order to make geodetic linear measurements. (5)

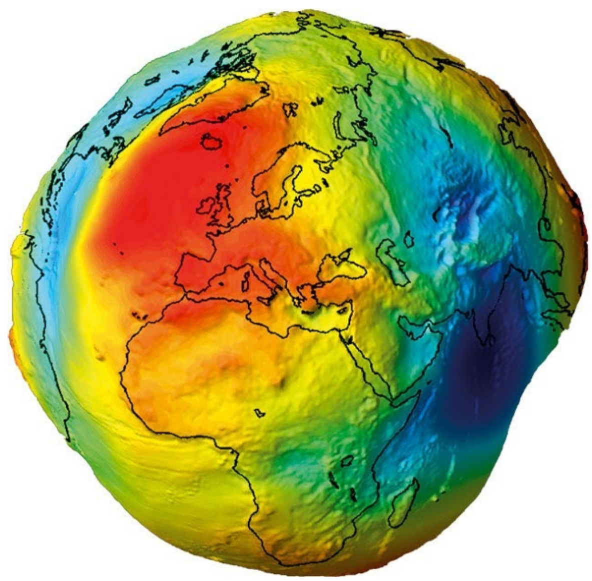
Spherical Coordinates – "Also called spherical polar coordinates, a system of curvilinear coordinates that are natural for describing positions on a sphere or spheroid. Define θ to be the azimuthal angle in the $x\,y$-plane from the *x*-axis with $0 \leq \theta < 2\pi$ (denoted λ when referred to as the longitude), ϕ to be the polar angle (also known as the zenith angle and colatitude, with $\phi = 90° - \delta$ where δ is the latitude) from the positive *z*-axis with $0 \leq \phi \leq \pi$, and r to be distance (radius) from a point to the origin. This is the convention commonly used in mathematics." (7)

Vertical Datum – "A surface of zero elevation to which heights of various points are referenced. Traditionally, vertical datums have used classical survey methods to measure height differences (i.e. geodetic leveling) to best fit the surface of the Earth." (8) NAVD 88 or North American Vertical Datum of 1988 is the current model used in the contiguous United States.

The ellipsoid is a model based of both the semi major and semi minor axis that approximates the shape of the Earth. What we know now is that the Earth is not uniform due to around 30 percent of its surface being covered by land mass. Many factors must be considered when determining the overall accuracy of a geodetic survey.

To clarify, the ellipsoid is a three-dimensional figure, in resemblance to a sphere of which the equatorial axis is a little longer than the polar axis. Ellipsoids help us simplify the math necessary to relate the model of the Earth's shape to a coordinate system grid. Ellipsoids are in essence a surrogate for geoids and are the imperfect approximations of geoids.

The next step to accounting for the reality of the Earth's surface is the geoid itself. The geoid signifies the global mean sea level. Meaning, the surface of the Earth, while using the geoid is equal to the level between the high and low tide marks. The geoid is important because it is able to take into account the uneven mass and shape of the Earth. (See Image 1.4)



(Image 1.4)

The uneven distribution of the surface can be explained by greater gravitational "pull" in certain portions of the Earth. The variations in gravitational force result in the geoid responding by constantly warping and moving in the form of an irregular shape with a wavy appearance. Geoid undulations, being distance above (positive) and below (negative) the geoid are responsible for difficulties in calculating the true shape of the Earth.

The Earth's surface is quite complex and oddly shaped so geodesists simplify the question by starting with the basic shape of a sphere. Essentially, the Earth is a squashed sphere (oblate spheroid). Geodesists then add in the mathematical models and arrive at the calculation of the ellipsoid.

The ellipsoid brings us closer to the Earth's true shape. It is created by rotating an ellipse around the shorter axis and matching the shape of the Earth (thinner at poles and greater at equator). Still, the ellipsoid is incomplete and does not provide an accurate take on the shape of the Earth.

We take into account the global mean sea level to arrive at the geoid. The geoid takes into account the lumpiness and uneven orientation of the Earth. If the geoid actually existed, the Earth's surface would perfectly add up to the level between low and high tide reference. The geoid does consider the Earth's gravitational fields, but we must put natural topography on top of this to achieve the true shape and size.

To measure the natural topography of the Earth, we would have to cover every inch of land, mountain and unique feature. This would take multiple lifetimes or further advancement in mapping technologies, which has yet to be achieved. New mapping methods such as LiDAR and Laser Scanning allow us to collect a great deal of mapping grade points in a short period of time.

LiDAR targets the Earth's surface and topographic features using a laser and calculates the time for a reflected light to return to the sensor. LiDAR was primarily used in the 1960's to map terrain and topography in aeronautics and aerospace. "It was only later, in the 1970s when this remote sensing technology was deployed on airborne sensors to map forests, oceans and the atmosphere. Perhaps, an unknown fact to most people is LiDAR technology was used by the National Aeronautics and Space Administration (NASA) for the Apollo moon missions." (9)

This technology is currently being utilized in space to collect accurate 3D models of the Earth for various reasons. In 2018, NASA developed and launched its (GEDI) program after developing a system to map forest ecosystems around the globe. "GEDI pronounced "Jedi," will soar over both the dark side and the light side of Earth at 17,150 miles per hour. Measurements of the height of foliage, branches, trees and shrubs below its path will yield new insights into how forests are storing or releasing carbon." (10)

While this method can produce a huge amount of data, tree canopy and other natural features prevent it from creating a perfect surface model of the Earth. "GEDI's LiDAR instrument sends laser pulses down to Earth, where they penetrate forests below the station's orbit at temperate and tropical latitudes. The laser beams ricochet off the first thing they hit, which can be a leaf atop a dense canopy, a protruding branch, or the ground from which the forest emerges. The energy returned to the GEDI telescope on the International Space Station will provide an intricate three-dimensional map of forest canopies." (10)

GEDI to date has the greatest point density and best resolution of any LiDAR sensor ever put into orbit. This data has two download options, one through NASA called Earthdata Search and the second through USGS called DATA TREE. "Datasets provided include precise latitude, longitude, elevation, height, canopy cover, and vertical profile metrics." (10)

Datum's are fundamentally how all geodetic survey work begins. The National Spatial Reference System (NSRS), which all of the survey measurements are based on, is composed of horizontal and vertical datums of the United States. These adopted United States datum's date back to 1927 (horizontal) and 1929 (vertical).

We can dissect the concept of a datum by thinking of it as sets of spatial data. Datum's also support other spatial information such as elevations, land use and population. These datasets are typically based off benchmarks based off an approximation of mean sea level, which are measured to establish baseline values.

"Geodesists and surveyors use datum's to create starting or reference points for floodplain maps, property boundaries, construction surveys, levee design, or other work requiring accurate coordinates that are consistent with one another. There are currently two main datum's in the United States. Horizontal datum's measure positions (latitude and longitude) on the surface of the Earth, while vertical datums are used to measure land elevations and water depths.” (11)

The first adopted vertical datum in the United States was the National Geodetic Vertical Datum of 1929 (NGVD 29), which at one time was called the Sea Level Datum of 1929. This datum was based off 26 different sites in the United States and Canada where tidal gauges were measured for mean sea level. In addition to the gauges, 246 closed level loops were ran (25 of them being at mean sea level).

In total, 106,724 kilometers of leveling was included in the establishment of the datum. Through differential leveling, 100,000 benchmarks were used in the adjustment and basis of the datum.

The name did not change to the National Geodetic Vertical Datum of 1929 until the National Geodetic Society adopted it in the 1970’s. Since it was a hybrid model based of adjustments, it is not truly mean sea level. Surveys prior to the establishment of the successor, North American Vertical Datum of 1988 (NAVD 88), will be roughly 1 foot different in elevation but this varies in different geographic locations.

The National Geodetic Society established a tool called Vertcon to convert between NGVD 29 and NAVD 88. The Army Geospatial Center also has a tool called Corpscon that will translate elevations between the two datum’s but the conversions are based off the NGS software. This Corpscon software also converts latitude and longitude coordinates to our current State Plane Coordinates. It calculates a Combined Factor is using horizontal and vertical values to translate coordinates to true ground distances.

The North American Vertical Datum of 1988 was established in 1991, including leveling observations from Canada, Mexico and the United States. This minimally constrained adjustment held one primary tidal benchmark. This benchmark was measured at mean sea level referencing the new International Great Lakes Datum of 1985. This benchmark, located at Father Point/Rimouski in Quebec, Canada was the basis for a leveling network on the North American Continent. (12)

This datum differs from its predecessor because it is based off a single point, ranging from Alaska, through Canada and across the contiguous United States. NAVD 88 became the official vertical datum in 1993 after being formally adopted by the National Spatial Reference System (NSRS).

One primary reason that vertical datum’s must be updated is that the ground will subside at times, which will lower the benchmark. Another issue is benchmarks will raise from the ground due to temperature and other weather phenomena. In addition, benchmarks can be disturbed by flooding, extreme hot and cold temperatures and ordinary wear and tear. One way to protect this is to drive your rod to refusal before attaching or affixing the cap.

It is important to pick durable materials when setting benchmarks. Most are standard and designed to stay in place as best as possible. Encasing the benchmark, embedding in concrete or bedrock is a good way to minimize disturbances. Shown below (Image 1.5) is a vertical benchmark that has been upset due to subsidence (sinking) of the surrounding area.


(Image 1.5)

The establishment of Static GPS measurements allows you to occupy multiple horizontal and/or vertical benchmarks at one time and tie down a level of accuracy based on the time of observation and satellites overhead. The processing software allows you to clean up and remove times where the PDOP (Position of Dilution of Precision – 3D position), HDOP (Horizontal Dilution of Precision) or VDOP (Vertical Dilution of Precision) is above acceptable measurement levels and focus on the times where your triangulation is precise.

Typically, your HDOP is going to be more accurate than your VDOP because the algorithms and triangulation is more suited for horizontal accuracy. GPS accuracy has greatly improved with other nations launching satellites into orbit and more signals for the GNSS receivers to use for calculation.

Leveling through these benchmarks is tedious and typically, more time consuming based on the length of measurement. When leveling, the surveyor must remember to keep the forward target at the same distance as the backward target in order to eliminate the curvature of the Earth in the measurement of a closed loop. These closed loops must go through a series of rigorous adjustments in order to disperse the error properly. Using a total station or theodolite, trigonometric leveling (vertical only) or traversing can produce horizontal and vertical positions at the same time.

Horizontal datums are a bit more complex then vertical datums due to the different adjustment methods. The U.S. Standard datum was the first established in the United States, the origin was located at Meades Ranch, Kansas. This datum uses the Clarke 1866 ellipsoid model for its basis.

“The transcontinental arc along the 39th parallel and connections to independent surveys on the west coast and the Gulf of Mexico led to readjustment and the release of a new official datum in 1901. The origin was moved in order to provide a better fit for the increased networks.” (13)

The U.S. Standard Datum was renamed the North American Datum in 1913 because Canada and Mexico chose to adopt it. After the western part of the United States set the framework for large triangulation arcs in 1926, it became evident that misclosures were disproportionate on shorter arcs. The readjustment of this network was then called the North American Datum of 1927 (NAD 27). "Laplace azimuths (geodetic azimuths derived from astronomic azimuths) were distributed through the network to provide orientation control." (13)

The current horizontal datum for the United States, Canada, Mexico and Central America is called the North American Datum of 1983 (NAD 83), even though it wasn't officially released until 1986. It is important to remember surveys prior to 1986 will not be in the current datum.

During the 1990's, states were conducting adjustments on the datum which was called the High Accuracy Reference Network (HARN). "Since then, the increasing accuracy and availability of GPS has required two adjustments of the entire network. These adjustments produced new realizations that are still on the same datum: NAD 83 (NSRS 2007), and NAD 83 (2011)." (13)

The North American Datum of 1983 is an Earth centered datum based or the Geodetic Reference System of 1980 (GRS 80)."NGS defined NAD 83 to replace the North American Datum of 1927 (NAD 27) because many survey observations had been completed since the 1930's including thousands of accurate Electronic Distance Measuring Instrument (EDMI) base lines, hundreds of additional points with astronomic coordinates and azimuths, and hundreds of Doppler satellite determined positions. However, it was difficult to add new these surveys to the geodetic network without altering previous work. Additionally, the Clarke Ellipsoid of 1866 no longer served the needs of a modern geodetic network." (13)

In the United States, we have had three different official reference ellipsoids: Bessel 1841, Clarke 1866 and the Geodetic Reference System of 1980. The "a" value corresponding to the Equatorial radius and "1/f" the inverse of the flattening of the ellipsoid.

1. Bessel 1841

a = 6,377,397.155 m 1/f = 299.1528128 (Years 1848 - 1880)

2. Clarke 1866

a = 6,378,206.4 m 1/f = 294.97869821 (Years 1880 - 1986)

3. Geodetic Reference System 1980 (GRS 80)

a = 6,378,206.4 m 1/f = 298.257222101 (Years 1986 to present)

(International Union of Geodesy and Geophysics Standard)

World Geodetic System 1984 (WGS 84) – Was not an official reference ellipsoid adopted by the United States. It was a reference coordinate system & ellipsoid in which Geodesists believe the error is less than 2 centimeters.

a = 6,378,137 m 1/f = 298.257223563

It was defined by U.S. Defense Mapping Agency (DMA) for GPS.

Below, (Chart 1.1) displays some other widely used reference ellipsoids around the world throughout history with given accuracies:

Reference ellipsoid name	Equatorial radius (m)	Polar radius (m)	Inverse flattening	Where used
Maupertuis (1738)	6,397,300	6,363,806.283	191	France
Plessis (1817)	6,376,523.0	6,355,862.9333	308.64	France
Everest (1830)	6,377,299.365	6,356,098.359	300.80172554	India
Everest 1830 Modified (1967)	6,377,304.063	6,356,103.0390	300.8017	West Malaysia & Singapore
Everest 1830 (1967 Definition)	6,377,298.556	6,356,097.550	300.8017	Brunei & East Malaysia
Airy (1830)	6,377,563.396	6,356,256.909	299.3249646	Britain
Bessel (1841)	6,377,397.155	6,356,078.963	299.1528128	Europe, Japan
Clarke (1866)	6,378,206.4	6,356,583.8	294.9786982	North America
Clarke (1878)	6,378,190	6,356,456	293.4659980	North America

Clarke (1880)	6,378,249.145	6,356,514.870	293.465	France, Africa
Helmert (1906)	6,378,200	6,356,818.17	298.3	Egypt
Hayford (1910)	6,378,388	6,356,911.946	297	USA
International (1924)	6,378,388	6,356,911.946	297	Europe
Krassovsky (1940)	6,378,245	6,356,863.019	298.3	USSR, Russia, Romania
WGS66 (1966)	6,378,145	6,356,759.769	298.25	USA/DoD
Australian National (1966)	6,378,160	6,356,774.719	298.25	Australia
South American (1969)	6,378,160	6,356,774.719	298.25	South America
GRS 80 (1979)	6,378,137	6,356,752.3141	298.257222101	Global ITRS
WGS 84 (1984)	6,378,137	6,356,752.3142	298.257223563	Global GPS

(Chart 1.1)

The World Geodetic System of 1984 (WGS 84) was built specifically as a unified global ellipsoid model after the mainstream use of Global Positioning Systems (GPS). This geodetic datum contains a reference ellipsoid, a standard coordinate system, altitude data and a geoid calculated from the center of Earth's mass. Coordinates generated from WGS 84 are displayed in latitude and longitude. This system was formally defined in 1987 and refined over time to reflect new gravitational models, which greatly improved accuracy.

A practical entry to geodesy is understanding how maps are created. We understand maps as two-dimensional images of specific regions of the Earth's surface. Maps are abstract, scaled and show us features of interest in relative orientations. Maps have many purposes and begin once positions of the features of interest are determined. The components of a map include position, coordinates, location, origin and a coordinate system.

Map distortions (Image 1.6) come from the conversion of a sphere to a flat surface. The four major spatial properties that are subject to distortion after this projection are:

Shape

If a map preserves shape, then feature outlines (like country boundaries) look the same on the map as they do on the earth. A map that preserves shape is *conformal*. Even on a conformal map, shapes are a bit distorted for very large areas, like continents.

A conformal map distorts area—most features are depicted too large or too small. The amount of distortion, however, is regular along some lines in the map. For example, it may be constant along any given parallel. This would mean that features lying on the 20th parallel are equally distorted, features on the 40th parallel are equally distorted (but differently from those on the 20th parallel), and so on.

Area

If a map preserves area, then the size of a feature on a map is the same relative to its size on the earth. For example, on an *equal-area* world map, Norway takes up the same percentage of map space that actual Norway takes up on the Earth.

To look at it another way, a coin moved to different spots on the map represents the same amount of actual ground no matter where you put it.

In an equal-area map, the shapes of most features are distorted. No map can preserve both shape and area for the whole world, although some come close over sizeable regions.

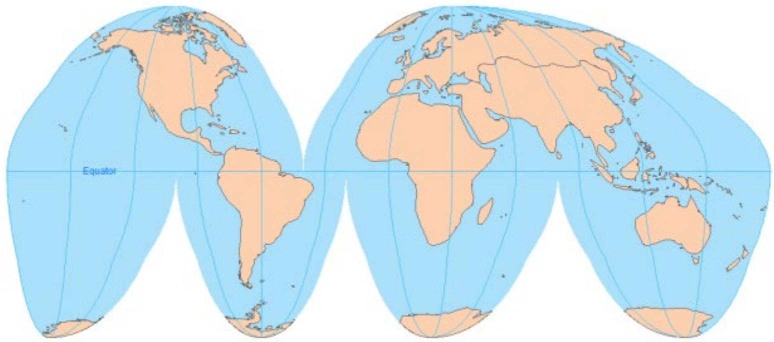
Distance

If a line from *a* to *b* on a map is the same distance (accounting for scale) that it is on the Earth, then the map line has true scale. No map has true scale everywhere, but most maps have at least one or two lines of true scale.

An *equidistant* map is one that preserves true scale for all straight lines passing through a single, specified point. For example, in an equidistant map centered on Redlands, California, a linear measurement from Redlands to any other point on the map would be correct.

Direction

Direction, or *azimuth*, is measured in degrees of angle from north. On the Earth, this means that the direction from *a* to *b* is the angle between the meridian on which *a* lies and the great circle arc connecting *a* to *b*. (14)



(Image 1.6)

Given the fact that you are unable to properly represent the Earth's surface in two dimensions, we must weigh which of the factors are more important for preservation and accuracy. A map projection is designed to systematically render a three dimensional ellipsoid of Earth to a two dimensional map surface. Many states choose to use either a Lambert Conformal conic projection or a Transverse Mercator projection based on the shape to minimize distortion. These projections are the basis for state plane zones.

"The need for the State Plane Coordinate System (SPCS) was great and its development nothing short of ingenious. For the first time ever, surveyors and engineers with limited computational power could extend geodetic control from a published monument to any project within feasible range with little modification to their normal field methods, all on a nationally recognized grid system." (15)

This grid system allowed the surveyor or engineer to make proper translations of coordinates from State Plane (grid) to Modified State Plane (ground) with less distortion due to the fact that each system was based off a map translation that best accounted for the true shape of the state. Each state defined principal meridians to which convergence is calculated. Though every point location has its own unique Combined Factor, when scaling from the Cartesian origin (0,0), surveyors and engineers were more equipped to replicate a prior survey with true ground distances.

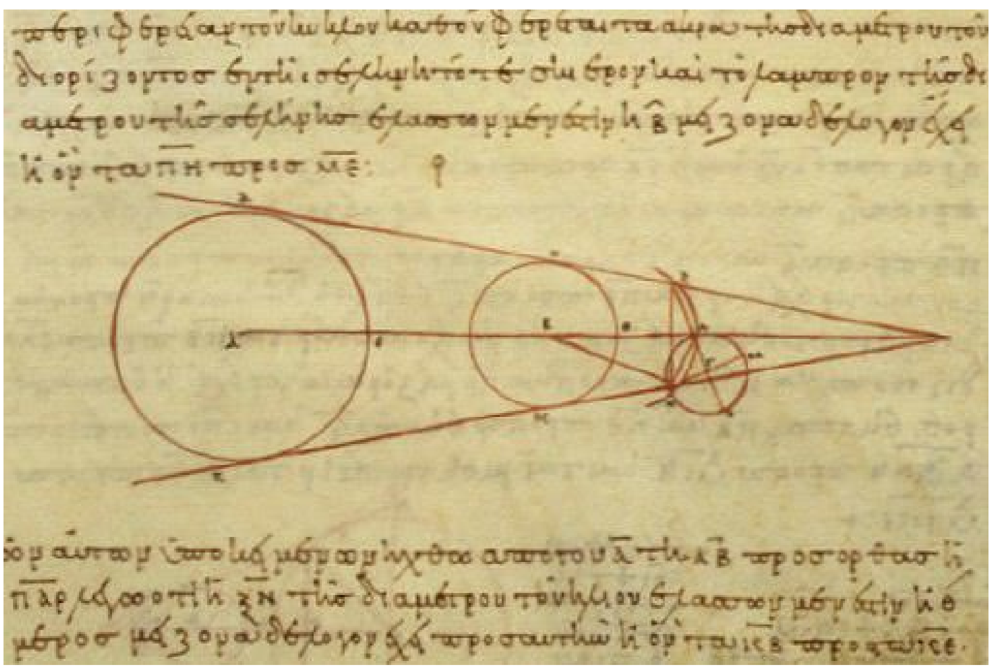
Accuracy of Past Earth Modeling

It has been a long process throughout history to discover the true shape of the Earth. The Ancient Greeks were fascinated by geometry and were the first to contemplate the theory of a spherical Earth. Aristotle (384–322 BC), an ancient Greek philosopher, may have been the first person to prove the Earth was spherical after Pythagoras first suggested it in 500 BC. Aristotle was the first to try to determine the circumference of the Earth at close to 40,000 miles (based off 400,000 stadia), which was quite a bit different from the accepted value of 24,901.461 miles at its largest, along the equator.

"Most people in Aristotle's time believed the earth was flat, but he did not agree. The Greek thinker realized that a lunar eclipse occurred when the Earth came between the sun and the moon. The shape of the Earth's shadow, Aristotle observed, was round. If the Earth were flat, its shadow would have a much different form.

Next, Aristotle considered the position of the North Star. The farther north you journeyed, the closer the North Star seemed to move to the middle of the sky. But if someone were to travel south of what we now call the equator, the North Star could not be seen at all. Finally, Aristotle watched ships sailing into port. He noticed that at a distance, he could see the tops of their sails before he saw the rest of the ship. Aristotle deduced that this was because of the curvature of the Earth. If we lived on a flat Earth, none of Aristotle's conclusions would be accurate." (16)

The earliest known definitive work of geodesy was done by Aristarchus of Samos (310-230 BC), an astronomer who worked on a geometric theory (Image 2.1) to determine ratios of the distance between the Sun and the Earth. "He claimed the Sun, not the Earth, was the fixed center of the universe, and that the Earth, along with the rest of the planets, revolved around the Sun. He also said that the stars were distant suns that remained unmoved and that the size of the universe was much larger than his contemporaries believed." (17) This idea of a Sun-centered universe with the Earth rotating is known as "heliocentric". His theory was based off one held by Heraclides Ponticus and the Pythagorean tradition.


(Image 2.1)

Another ancient Greek, based in Egypt, named Eratosthenes (276 BC -194 BC) is credited with the first physical calculation of the Earth's circumference. "Eratosthenes knew that on the first day of summer, the Sun passed directly overhead at Syene, Egypt. At midday of the same day, he measured the angular displacement of the Sun from overhead at the city of Alexandria - 5000 stadia away from Syene. He found that the angular displacement was around 7.2 degrees - there are 360 degrees in a circle, making 7.2 degrees equivalent to 1/50 of a circle. Geometry tells us that the ratio of 1/50 is the same as the ratio of the distance between Syene and

Alexandria to the total circumference of the Earth. Thus the circumference can be estimated by multiplying the distance between the two cities, 5000 stadia, by 50, equaling 250,000 stadia." (18)

For its time, Eratosthenes measurement was extremely accurate given the fact that he was within 1 percent of today's accepted value. He was able to achieve a high-level measurement from a relatively small portion of the Earth's surface.

Another early contributor was an Indian mathematician named Aryabhata (AD 476–550). He was a mathematical astronomer, described the Earth as being spherical, and noted that the Earth rotated on its axis. "Aryabhata also worked out a value for pi that equates to 3.1416, very close to the approximations still used today. Using this value, he was able to calculate that the Earth had a circumference of 24,835 miles. This is correct to within 0.2%, and remained the best figure available well into medieval times.

While working on the calculation of pi, Aryabhata may also have discovered that number's irrationality. The relevant text is inconclusive on this point, but if he did establish the irrational nature of pi, he beat the first European mathematicians to do this by many hundreds of years.

The *Aryabhatiya* also contains solid work regarding the solar system. It states correctly that the light cast by planets and the moon is caused by sunlight reflecting off their surfaces, and that all planets follow elliptical orbits. Aryabhata was also able to describe accurately the processes that lead to both solar and lunar eclipses." (19)

The theory of precession meaning the change in orientation of the rotational axis of Earth is also credited to the Greeks. Hipparchus (190-120 BC), a Greek Astronomer, compared ancient observations over a century earlier to his own to determine that the Earth does not rotate perfectly on a fixed axis. The tilt of the earth stays very close to 23.4 degrees with an ever-changing orientation.

Since observations began in 1899, with the establishment of the International Latitude Service (a branch of the International Geodetic Association), scientists have been perplexed by the spin axis wobble in Earth's rotation. At this time, they discovered that every six to fourteen years, the spin axis wobbles twenty to sixty inches (0.5 to 1.5 meters) of the Earth's general direction of drift both east and west. (20) The farthest away from the axis running through the north and south poles was measured at 37 feet.

Due to the loss of ice on North America from the last ice age, the mass underneath the continent is pulling the spin axis closer to Canada a few inches every year. Scientists have also suggested the loss of mass from Greenland and Antarctica (melting ice) could be causing the eastward shift in the spin axis. This is eye opening but does complete the puzzle of why the Earth wobbles.

(Image 2.2)

What the researchers have proposed is that the major answer is the deficit of water in Eurasia, areas of the Caspian Sea and the Indian Subcontinent. This came as a surprise to the researchers but explained more than they were first led to believe.

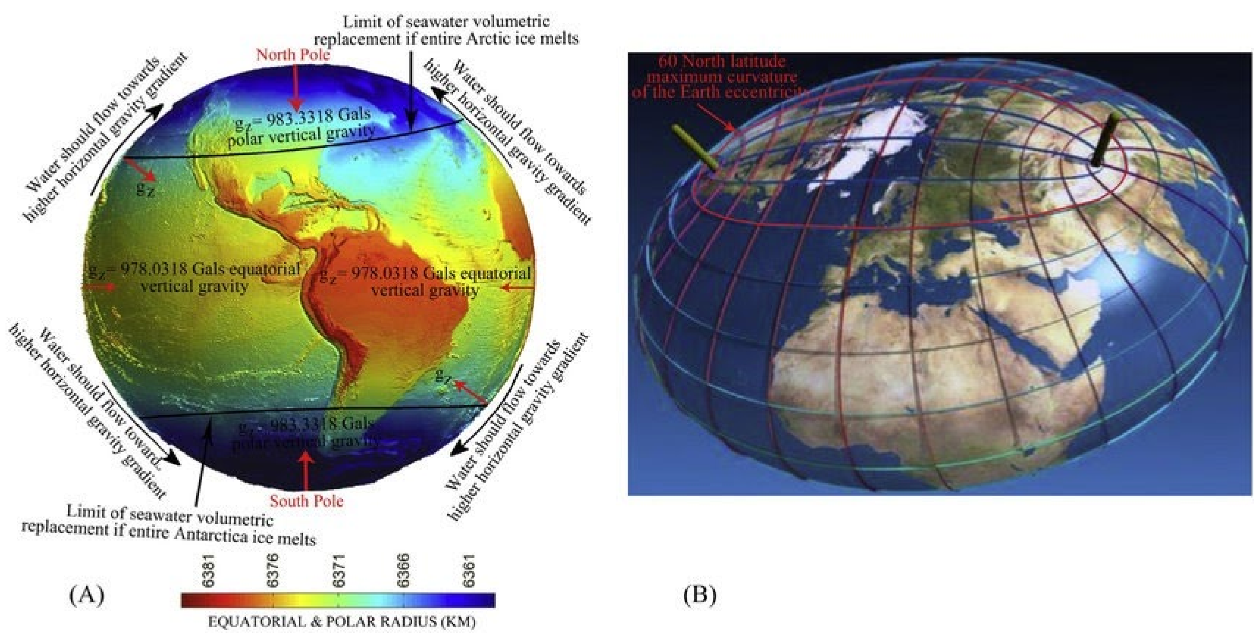
The region has been experiencing water mass loss because of drought as well as the aquifers being depleted. The confusion is in the fact that the loss of water in Indian and the Capsian Sea is nowhere near the change in the major ice melts in Greenland and North America, but is more influential.

Still, we need more explanation to why the polar ice melts have little to no relationship to the wobble of the Earth. When the scientists put graphs of the same period to display the east-west wobble and of continental changes in water storage, they have surprising similarities. Thus, changes in polar ice are insignificant while water on land changes are. This is to say, dryer years in Eurasia actually relate to east swings while wetter years relate to west swings. (20)

For the purpose of measuring the Earth, triangulation became more widely used during the 16th and 17th century and a preferred method of measurement. Using triangulation, we determine positions by taking two fixed points with a known distance and measure the angles to the point we wish to know.

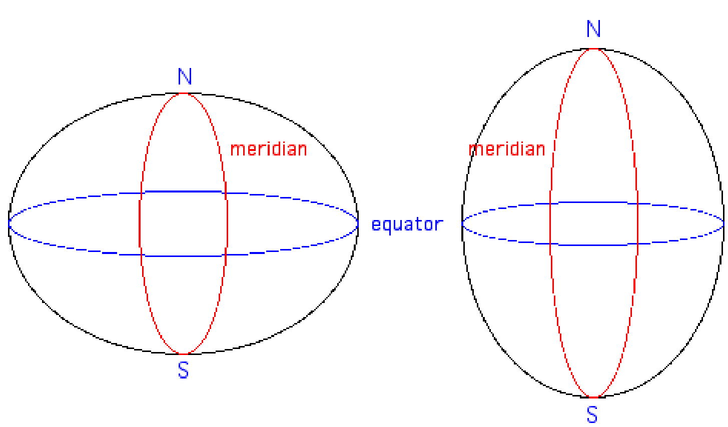
The 17th and 18th centuries were a time of debate and battle over the shape of the Earth. Many believed their approach and understanding was superior to the other. The French and the English staged expeditions to see who was correct.

The true shape of the Earth was a long held debate between Enlightenment Age scholars René Descartes and Isaac Newton. In England, Sir Issac Newton (Universal Theory of Gravity) described the Earth as oblate (flat at the poles), in the “Principia”, appearing in 1687. Newton described the idea of strong and forceful attraction (gravity) that was always operating at a distance was slightly less near the equator. (21) Newton was able to solve the shape of the Earth from calculations at his desk.



(Image 2.3)

In France, scientists of the Academy of Sciences suggested that the Earth was prolate (egg-shaped). The French Astronomer (Cassini) proposed the opposite of Newton and did so by arc measurements (elongated at poles). Followers of Rene Descartes (the French) believed his theory of vortices could explain the prolated shape of the Earth.



(Image 2.4)

Rene Descartes is well known for his contribution of the Cartesian plane, a rectangular coordinate system divided into quadrants that associates each point in the plane with a pair of numbers. This allows us to specify points defined by a plane using a set of coordinates. This being what plane or two dimensional survey measurements are now based on. This has significantly improved our understanding of the visible and spatial world and given us a way to plot points.

Considering the time of discovery, knowing the exact shape of the Earth was much greater than an academic interest and discussion. If a power knew the exact shape of the Earth, they would be best equipped to navigate and potentially control the oceans. This would secure power for the empires competing against one another. (21) This was important for expansion, as proper navigation would lead to the ability to establish colonies and gain access to different plants and materials.

This is an important time in history, not only for geodesy but also for all of science. The French government’s ten year mission to the Spanish colony of Peru (modern-day Ecuador) was the first international scientific expedition. The expedition of 20 French and Spanish scientists began in 1735, with the task of measuring the Earth and calculating the precise length of a degree of latitude at the equator.

(Image 2.5)

By 1739, the survey measurements were complete and the length of the meridian arc was equal to three degrees at the Equator (in Quito). At this time, another expedition to Lapland led by Maupertuis had finished and the work in the north already proved the Earth is flattened at the poles contrary to the conclusion previously proposed by France. The reason the party stayed longer in Ecuador was to resolve errors in the observations of astronomical figures.

During the time of experimentation, it was not widely known that the Earth’s motion around the sun caused very small variances in the location of stars that were used as fixed latitudes.

Fortunately, the group did figure out a correction, thus requiring nearly seven months of recalibration. The unparalleled determination and commitment to the mission is remarkable in itself. As for the measurements themselves, the principle the team relied on was triangulation.

The basic idea was to use wooden poles and measure twenty-foot lengths for longer surveys of many miles at a time. By knowing one side of a triangle in length, you can measure two of the angles and reconstruct the remaining measurements of a triangle. The team continued in this way to build up chains of triangles up to 200 miles in length.

The instrumentation that was used is called a quadrant. Consisting of a dense cast iron piece of metal with telescopes that endured the harsh journey across the oceans and the mountainous landscape. When gazing into the attached telescopes they were able to observe up to a mile away and at the same time differentiate between two points about six inches from each other.

Upon measuring distance, they combined their findings with sighting stars in order to know precise latitude at both the furthest southern and northern points. Dividing the latitude by the length gave them the distance of a degree of latitude while at the equator. After doing so, the findings were compared with those in France and this provided the figure of the Earth.

After the expeditions, both field parties returned to France to officially present their findings. The mission revealed some marveling facts about our planet and changed geodesy forever. The 1730's French expeditions uncovered that the Earth bulges at the equator making it an oblate slightly off-shaped sphere.

Newton theory was proven correct by the finding of the expeditions, and the Earth was deemed an oblate spheroid. This grand achievement during the colonial age set forth a firm marker of understanding for the world we live in. This allowed us to build upon the model and deepen our understanding of the Earth and its mechanics.

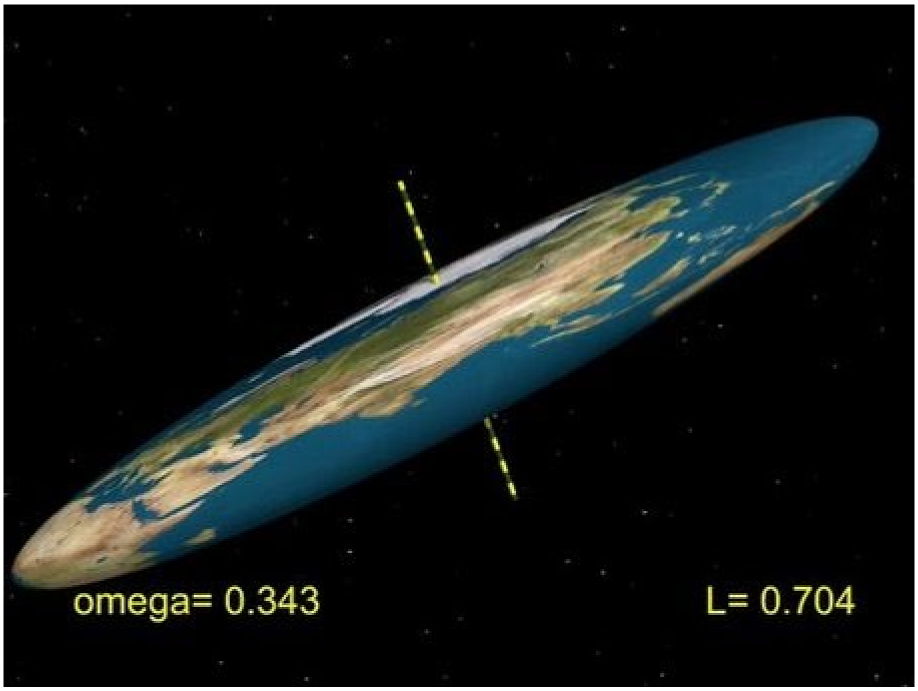
By today's standards, the measurements were remarkably accurate. The measurements were within 50 yards over the distance of a degree of latitude (almost 69 miles). This information did a great deal for the scientific world as well as commerce and navigation.

The discovery made maps more accurate and significantly improved navigation that allowed ships to return or arrive at ports with greater ease. The seas were much easier to sail and commerce and international trade benefited greatly from this. The international cooperation and teamwork was another hallmark that paved the way for many more collaborative scientific missions to come. (22)

After the basic shape of the Earth was solved, mathematicians started to setup and create models of the Earth. In 1742, Colin MacLaurin (1698-1746) published "A Treatise on Fluxions" which contained a study of the shape of rotating bodies. He believed that over time the flattening of the Earth would increase.

"MacLaurin shows that, as the angular momentum increases, the Earth will get ever more flat. The shape is an ellipsoid with two equal axes, rotating around the short axis. The ellipsoid becomes a disc with an ever-increasing radius. The rotation speed first increases, but the speed reaches a maximum and will then decrease. As the radius of the disc continues to grow and trends toward infinity, the rotation speed will trend toward zero: *L* can be expressed as *L=Ï‰.I*, where *I* is the *moment of inertia*. For a constant mass, the moment of inertia of any object will get larger and larger as the object takes on a shape where a radial dimension becomes larger and larger. Therefore the rotation speed *Ï‰* must go to zero for a finite *L* and an ever increasing radius." (23)

Over time, the radius at the equator would create a surface resembling a flat disc (Image 2.6). The actual rotation speed of the Earth corresponding to a value *Ï‰* of 0.6 with an actual angular momentum value *L* equaling close to 0.24.



(Image 2.6)

Carl Jacobi created an ellipsoidal Earth model in 1834. He stated that the Earth could be a stable configuration in the shape of an ellipsoid with three unequal axes. Also stating that the angular momentum as the cause of the ellipsoidal shape. "This leads to doing *harmonic analysis* on the ellipsoid, analogous to *spherical harmonics* on the sphere. We will then encounter the functions of Lamé: (*a*<*b*<*c*)

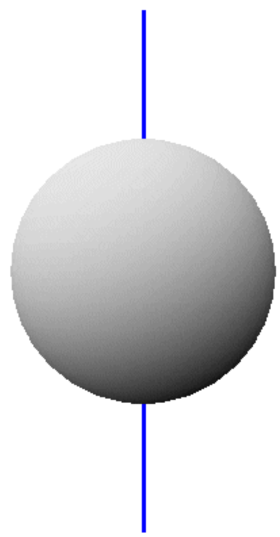
$$\frac{x^2}{a^2-\lambda^2}+\frac{y^2}{b^2-\lambda^2}+\frac{z^2}{c^2-\lambda^2}=1$$

This formula describes an ellipsoid for Î»<*a*, a one-sheeted hyperboloid for *a*<Î»<*b* and a two-sheeted hyperboloid for *b*<Î»<*c*. We get a family of surfaces for a given *a*, *b* and *c* that are all perpendicular to each other." (23)

Henri Poincare published an article in *Acta Mathematica* in 1885 that further described Jacobi's ellipsoidal model. He described how the ellipsoids encounter bifurcation points and the shape is conformed to resemble a pear.

To grasp the concept of geodesy, spherical geometry provides the basis of measurement defined as the study of figures on the surface of a sphere. The sphere being a closed three-dimensional surface in which a set of points are equidistant from the center of the sphere.

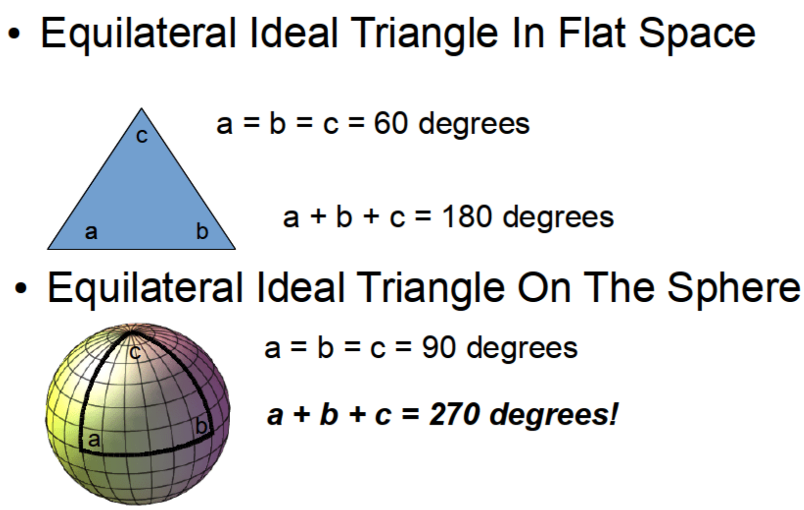
“An arbitrary straight line (not lying in the sphere) and sphere in three dimensional space can either (a) not intersect at all; (b) intersect at one point on the sphere, when the line is *tangent* to the sphere at the point of intersection; or (c) intersect at precisely two points, when the line passes through the sphere. In this particular case, if the line passes through the center of the sphere and intersects the sphere's surface in two points, the points of intersection form the *antipodes* of the sphere. The North and South Poles (both the magnetic and geographic poles) are examples of antipodes on the globe.” (24)



(Image 2.7)

This sphere, being made up of Great Circles, which share the same radius and center. These circles of intersection can be obtained by passing a flat surface through the sphere. “Imagine a line from the North to the South Pole, passing through the center of the globe. The circles of intersection formed by the globe and a plane perpendicular to this imaginary line make up the globe's lines or parallels of latitude. Each of these circles of intersection, with the exception of the Equator at which point the plane is at the midpoint of the pole-to-pole line, are called *small circles* precisely because their radii measure less than the Earth's radius *R*.” (24)

Spherical Triangles are areas enclosed by the lines of the arcs of three great circles on the surface of a sphere. The interior angles of an equilateral planar or Euclidean triangle always adds up to 180 degrees, while an equilateral spherical triangle has interior angles equaling 270 degrees. The amount over 180 degrees, measured from the sum of the spherical angles is known as Spherical Excess. A spherical angle or a lune is formed at the intersection of two arcs of great circles.

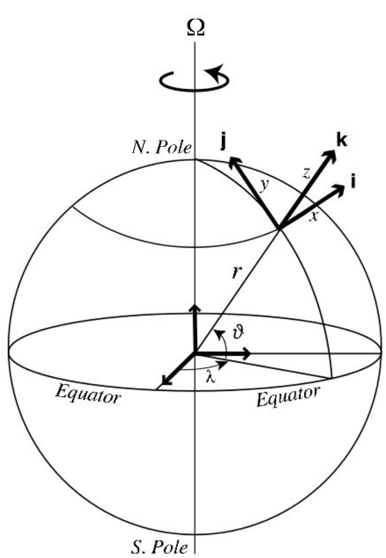


(Image 2.7)

"Like their angles, the length of the sides of a spherical triangle are measured in degrees or radians. Specifically, the length of a side of a spherical triangle equals the measurement of its opposite angle. In geography, the angle between two meridians of longitude equals the same number of degrees as the arc cut off by these lines of longitude on any circle of latitude. So, in the above figure, each of the sides measures 90° since each of their opposing angles measures 90°.

The most useful application of spherical triangles and great circles is perhaps calculating the shortest-distance route between two points on the globe. This application is often referred to as the *solution of spherical triangles* and makes extensive use of the well known Cosine Law for triangles on a plane: $c^2 = a^2 + b^2 - 2ab \cos C$. Given two sides of a spherical triangle and the angle between these sides, the solution for a spherical triangle yields the length of the third side." (24)

Spherical coordinates define a point in three dimensions on the surface of the plane. The radius being a straight line from the center to a point on the surface as shown below:



(Image 2.8)

Understanding spherical geometry and trigonometry is the fundamental basis of Modern Terrestrial Reference Systems. In North America, we typically use three different three-dimensional reference systems being NAD 83, WGS 84 or the International Terrestrial Reference System (ITRS), which is more suitable for achieving higher positional accuracy. These are all very close, but different in how they have been defined or realized. A "reference frame" is the realization of an individual reference system.

"The modern approach to defining a 3D terrestrial reference system may be divided into four steps. The first step links the axes of a 3D Cartesian coordinate system to a configuration of physically measurable locations on or within the Earth. As a result, the location and orientation of the three coordinate axes are defined. The second step relates the concept of distance to physically measurable quantities whereby a unit of length is introduced. The third step introduces an auxiliary geometric surface that approximates the size and shape of the Earth. Finally, the fourth step addresses the question of how Earth's gravity field contributes to the notion of position, and especially that of height. We shall be concerned here with only the first three steps, thus focusing on the geometric aspects involved in defining a reference system." (25)

The National Geodetic Survey is planning to establish new national reference frames in 2022 to replace the current North American Vertical Datum of 1988 (NAVD 88) and the North American Datum of 1983 (NAD 83). These are being replaced because NAD 83 is non-geocentric by 2.2 meters (approximately) and NAVD 88 is biased by 0.5 meters and tilted by 1 meter coast to coast.

xGeoid

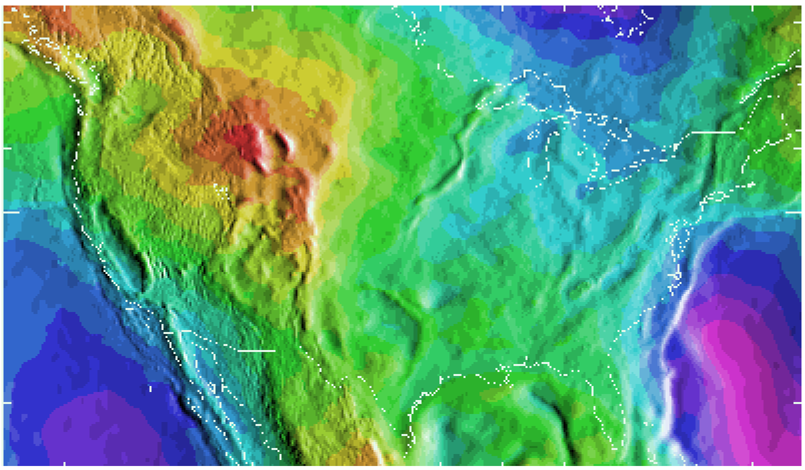
The xGeoid or Experimental Geoid project by the National Geodetic Society (NGS) started in 2014 and ran through 2020. These yearly models were derived to determine precise heights in the National Spatial Reference System (NSRS). The focus was to approximate mean sea level with respect to the Earth's gravitational field. Using the gravity data from the latest satellite gravity models, along with terrestrial gravity and airborne gravity, NGS is redefining the American Vertical Datum project.

"The purpose of the models is to demonstrate the geoid improvement over areas where the GRAV-D data are available. The xGeoid's provide a preliminary but increasingly accurate view of the changes expected from the scheduled 2022 release of a new geopotential reference frame. The purpose of these annual geoid models is twofold:

1. To compute the geoid using present-day satellite gravity models and airborne gravity data, so as to prepare NGS for the final geoid modeling in 2022 using the complete airborne gravity data set and the latest satellite gravity models.

2. To provide to the stakeholders of the North America a perpetually improving and converging view of what the final geoid model will look like as we approach its use in replacing NAVD 88 in 2022." (26)

The geoid is the vastest data set of the dynamic structure of the Earth's interior. Shown below (Image 3.1) is the Yellowstone Hot Spot, which is thought to be a plume structure that rises through the Earth's mantle. After the planned adaptation in 2022, models will be under an inch in most parts of the county.

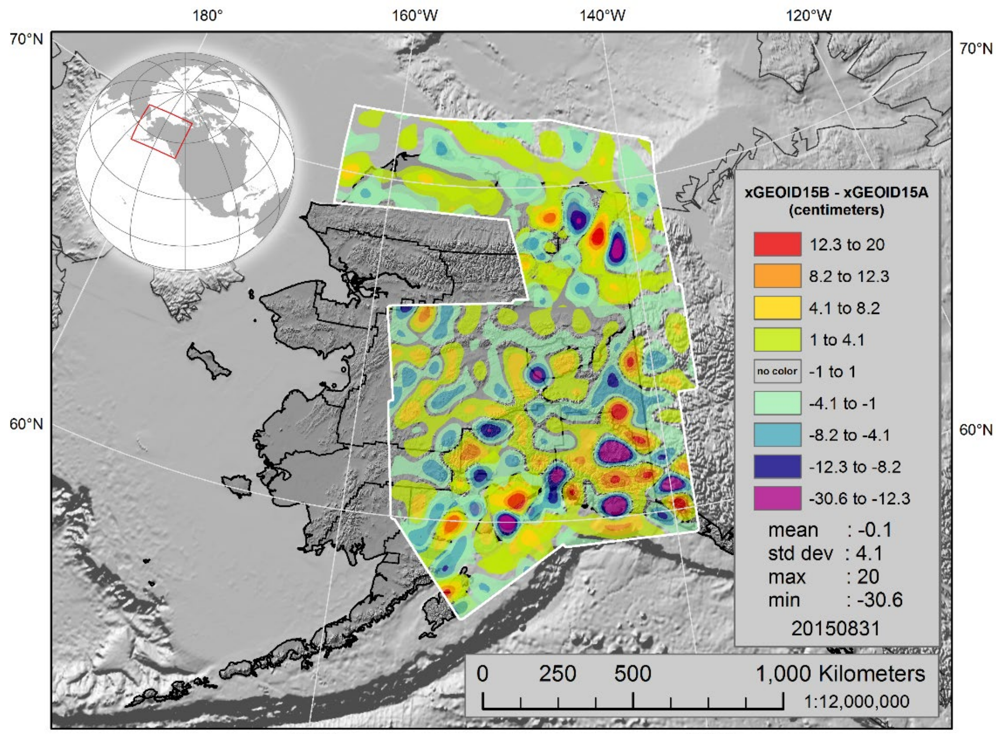

(Image 3.1)

"The xGeoid14A and xGeoid14B models represent a first effort in producing geoid height models that span all of Alaska, Hawaii, the Conterminious United States (CONUS), and Puerto Rico and the USVI (PRVI). Being developed from a single model means that derived heights will reference the same datum across all four regions." (26)

The xGeoid14B model differs from Geoid12A and USGG2012 because it included aerogravity. The use of this new data set showed the limitations of previous models and problems with the existing NGS terrestrial data set. This is different from the other data sets in some regions because aerogravity has a different gravitational field then the previously used surface gravity and airborne gravity data sets.

"This is necessary because a great deal of the metadata associated with the surface gravity data have been lost. This data was collected over a period of about 70 years with the bulk of it being over 50 years of age. These data could be used to produce a geoid model valid for 50-60 years ago but not today. Aerogravity can be used to account for the slow, systematic changes that have occurred over time as well as any blunders that may have occurred." (26)

The xGeoid15A and xGeoid15B were created next. The xGeoid15A incorporated the GOCO5S satellite gravity model with EGM2008, NGS's Terrestrial gravity data and 3" digital elevation model. Shown below (Image 3.2) are the difference in the two geoid models over Alaska.

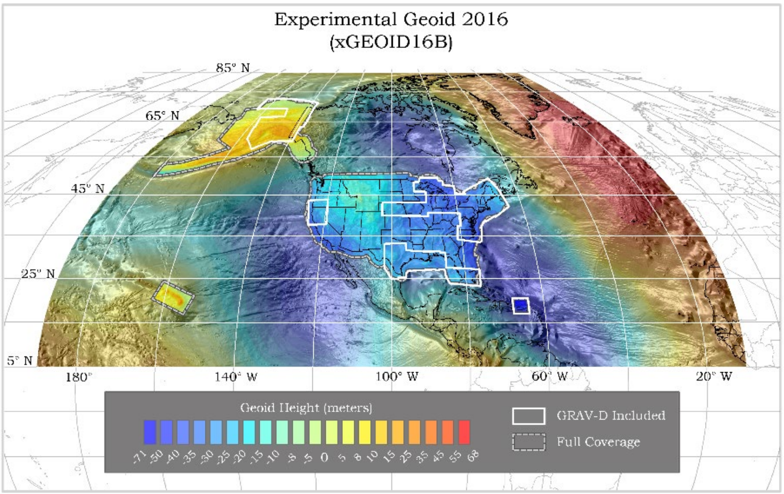


(Image 3.2)

"The reference (global spherical harmonic) gravitational model for xGeoid15A was computed by augmenting EGM2008 with the GOCO05S satellite gravity model, which includes the last 14-month low orbital GOCE data. This year's experimental procedure combined EGM2008 and GOCO05S in the space domain, unlike last year's combination of model coefficients in the frequency domain. This experimental procedure operated on global 5'x5' grids of gravity disturbances that had been generated from each of the two models. For this approach, application of non-stationary, local error models to these two 5'x5' grids of disturbances allowed them to be combined into one, composite 5'x5' grid. Harmonic analysis of this composite grid yielded a combination spherical harmonic gravitational model (Nmax=2190). Low-degree (n < 50) distortions in this combination model were then corrected with GOCO05S, yielding the final reference model for xGeoid15A. This final model was designated 'REF15A'. Additionally, a 1'x1' reference gravitational geoid was computed from the REF15A model, using the same procedure to that was used for the EGM2008 gravimetric geoid." (26)

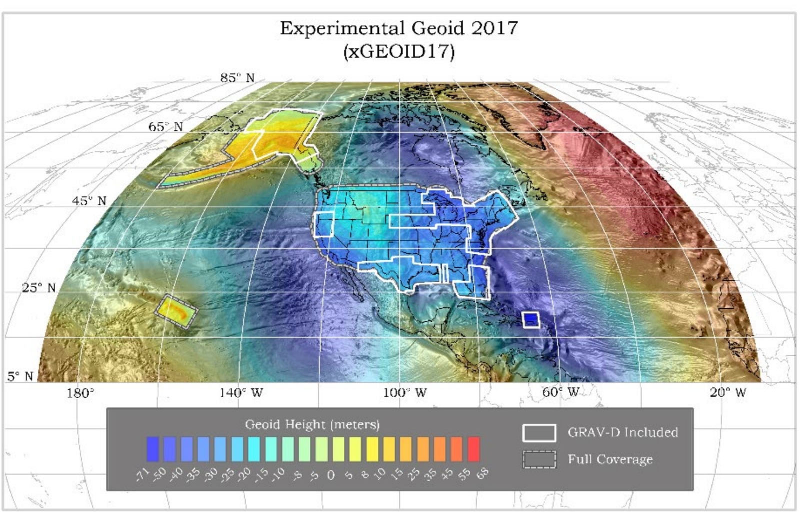
The reference model for xGeoid15A was then combined with NGS terrestrial data in which residual gravity anomalies were set to a 1' by 1' grid. The creation of xGeoid15B was the same as xGeoid15A, but included GRAV-D airborne data. Each experimental year followed suit with the B version containing the additional data.

xGeoid16A used the same data set as xGeoid15A, but adjoining and/or overlapping surveys were processed together with a single adjustment. This allowed for survey lines to contribute to adjacent and overlapping surveys. The main difference in xGeoid16B was an area over Lake Michigan. "For xGeoid16B, the REF16B model was used to identify and mitigate egregious biases in a few of the ship-track surveys over Lake Michigan. The 'de-biased' ship-track data was then used as NGS terrestrial data input for xGEOID16B over Lake Michigan." (26)



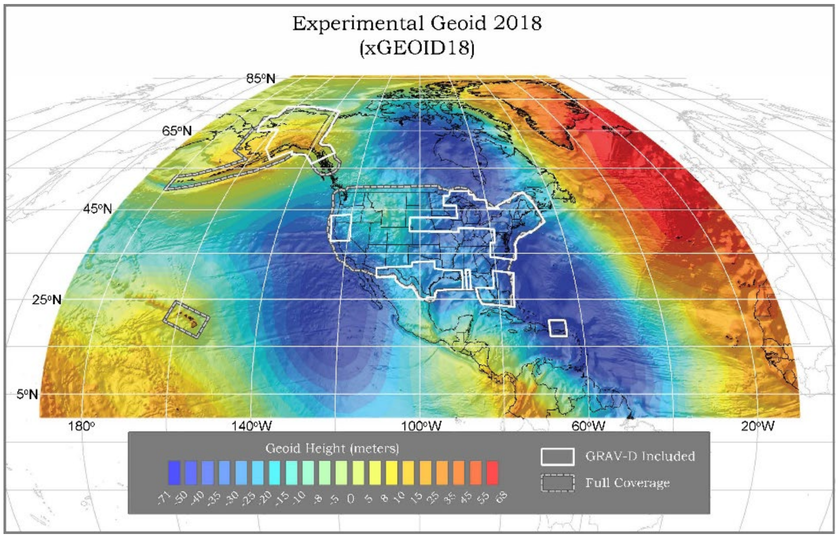
(Image 3.3)

The data set for xGeoid17A is more robust than the previous two. This set included the GOCO05S satellite gravity model, NGA or National Geospatial-Intelligence Agency terrestrial gravity data, NGS terrestrial gravity data to supplement coverage, Altimetric gravity anomaly DTU13 and 3" digital elevation model. "The terrestrial gravity data was separated by survey numbers and de-biased using the satellite gravity model GOCO05S. This procedure works only for surveys in comparable spatial distribution to the spatial resolution of satellite gravity model (100 km). For surveys covering smaller areas, a local Radial Basis Function (RBF) was used in a second de-biasing step." (27) xGeoid17B, like the previous models was created in the likeness of xGeoid17A, but added in the GRAV-D airborne data from xGeoid16B and additional airborne data. We can see a larger portion of GRAV-D data in xGeoid17B (Image 3.4) from the previous model.



(Image 3.4)

xGeoid18 models are similar to xGeiod17 except the data extends to the equator (Image 3.5). No new GRAV-D airborne data was incorporated for 2018. Guam, Central Northern Marianas Islands and American Samoa was incorporated in the 2018 models (Table 3.1).



(Image 3.5)

Geoid Grid:	Latitude Range:	Longitude Range:	Min.	Max.	Mean	Std. Dev.
Guam/Central Northern Marianas Islands	11° to 22°	143° to 148°	25.725	55.892	44.420	7.913
American Samoa	-16° to -10°	186° to 193°	16.711	42.428	24.822	4.910

(Table 3.1)

“For these two geoid models (xGeoid18A and xGeoid18B), we utilize PGM17 to degree 2190. This reference model is a preliminary model developed by NGA, which will ultimately become EGM2020. This reference model was selected instead of NGS-developed reference models due to superior fits with GPS/leveling data on these islands.

Input datasets:

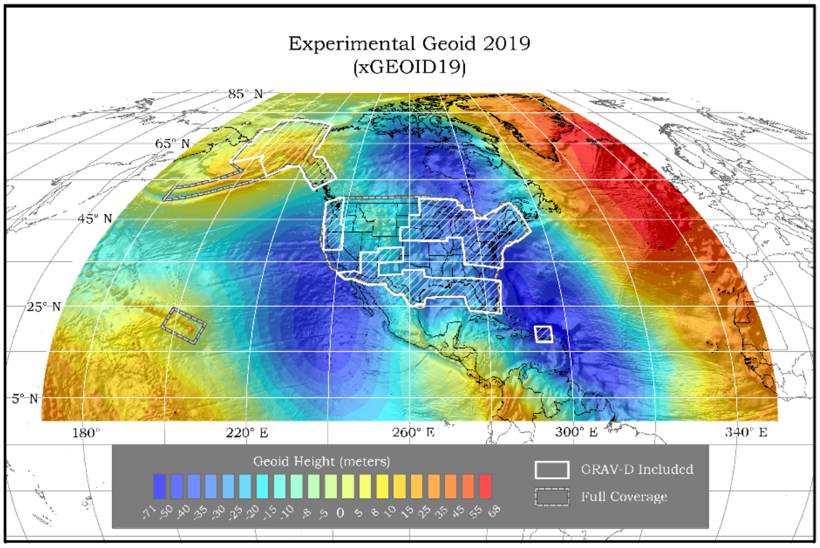
• Reference Model: PGM17 to degree 2190.

• Terrestrial Gravity Data: NGA gravity data supplemented with NGS gravity data. This data includes shipborne gravity data, which was used in the two geoid models. NGS acquired surface gravity measurements in 2017 on the islands of Guam, Rota, Tinian, Alamagan, Pagan, Ascunsion, and Maug in the Central Northern Marianas’ Islands. The more northern islands previously had no surface gravity data so a handful of observations are providing a major contribution.

• Altimetric Gravity Data: DTU15 altimetry-derived gravity data

• DEM Data: SRTMv4.1” (28)

xGeoid19A and XGeiod19B (Image 3.5) differ quite a bit from the previous version because it incorporated a time dependent component provided by the xDGeoid19 model produced by NGS, which was solely based from data provided by NASA's GRACE mission. The D standing for Dynamic, which will be included in the new North American-Pacific Geopotential Datum (NAPGD 2022). These two also incorporate an experimental deflection of the vertical called xDeflec19.

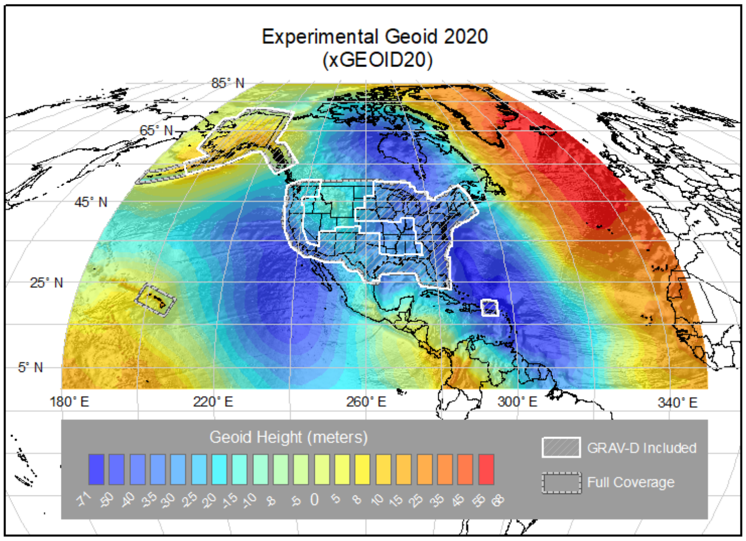


(Image 3.5)

"The xGeoid19 models cover the entire region of North America, including the continental United States (CONUS), the states of Alaska and Hawaii, the U.S. territories of Puerto Rico and the U.S. Virgin Islands, and neighboring countries such as Canada and Mexico. The exact geographic extent of the area is from latitude 85 degrees N to the equator in the north-south direction, and from longitude 170 degrees E to longitude 350 degrees E in the east-west direction. xGeoid19 is based on a 1'x1' gravity grid and a seamless 3''x3'' digital elevation model (DEM) derived from the North American common gravity and DEM database that has recently been compiled by NGS. The xGEOID19 model is computed from the xGEOID16RefA coefficient model, which is a combination of EGM2008 and GOCO05s up to degree and order 2160." (29)

The xGeoid20 models (Image 3.6) are the latest experimental models included in building the new North American-Pacific Geopotential Datum. These were the first to use a combination of models computed by the National Geodetic Survey (NGS) and Candian Geodetic Survey (CGS), unlike the previous years the A and B models include differences in both the addition of GRAV-D data and methodology of calculation. This model, like xGeoid19, uses the dynamic satellite data from NASA's GRACE mission, but also uses airborne measurements of ice loss in Alaska and the Level 1B regression mascon solution by NASA called the Goddard Model.

New experimental deflection of the vertical (xDflec20) and experimental dynamic geoid (xDGeoid20) are included in the calculation of xGeoid20A and xGeoid20B. The dynamic model, produced by NGS, within the Geiod Monitoring Service (GeMS). This was built for NGS to obtain model time dependent changes in both the geoid and geopotential.



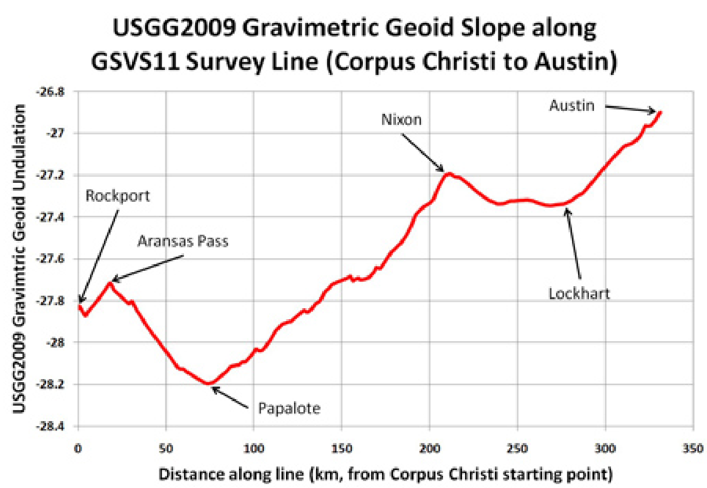
(Image 3.6)

Along with the different computed models, NGS has completed three Geoid Slope Validation Surveys (GSVS) to determine the accuracy of gravity based models and to quantify the value of data acquired from the GRAV-D project. The three surveys took place in Texas (2011), Iowa (2014) and Colorado (2017).

The Geoid Slope Validation Survey of 2011 (Texas) covered a 300km stretch of highways running north-south from Austin to Corpus Christi (Image 3.7). This stretch was picked because it was relatively flat and gravimetrically uncomplicated. This area was close to the geoid and under the existing GRAV-D surveys. The following was measured from the line:

1. Differential orthometric heights and differential ellipsoid heights from leveling and GPS campaigns, respectively (both minimally constrained).

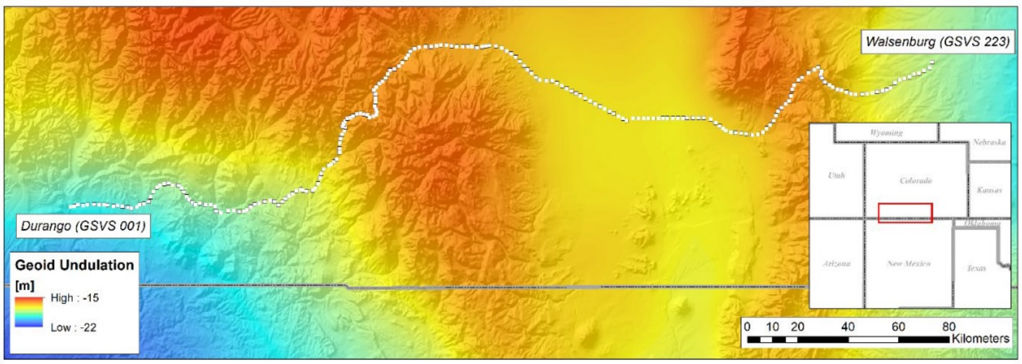
2. Astro-Geodetic deflections of the vertical from observations with the Swiss DIADEM camera. (30)



(Image 3.7)

The Geoid Slope Validation Survey of 2014 (Iowa) covered a 325km stretch of highways running east/west from Denison to Cedar Rapids. This area was ranged from 740 feet to 1,440 feet above mean sea level which included static or long session GPS, first order geodetic leveling, gravity calculations, astro-geodetic deflection calculations, airborne gravity and real time kinematic GPS observations in order to establish values on fixed points across the project. (31)

The most recent Geoid Slope Validation Survey of 2017 (Colorado) was performed to evaluate the accuracy of the geoid in a rough, high elevation region that was gravimetrically difficult. The 360km line ranged in elevation from 6,200 feet to 10,800 feet running more or less east/west from Walsenburg to Durango. The measurements were similar to the survey done in 2014, but more in depth. (32)



(Image 3.8)

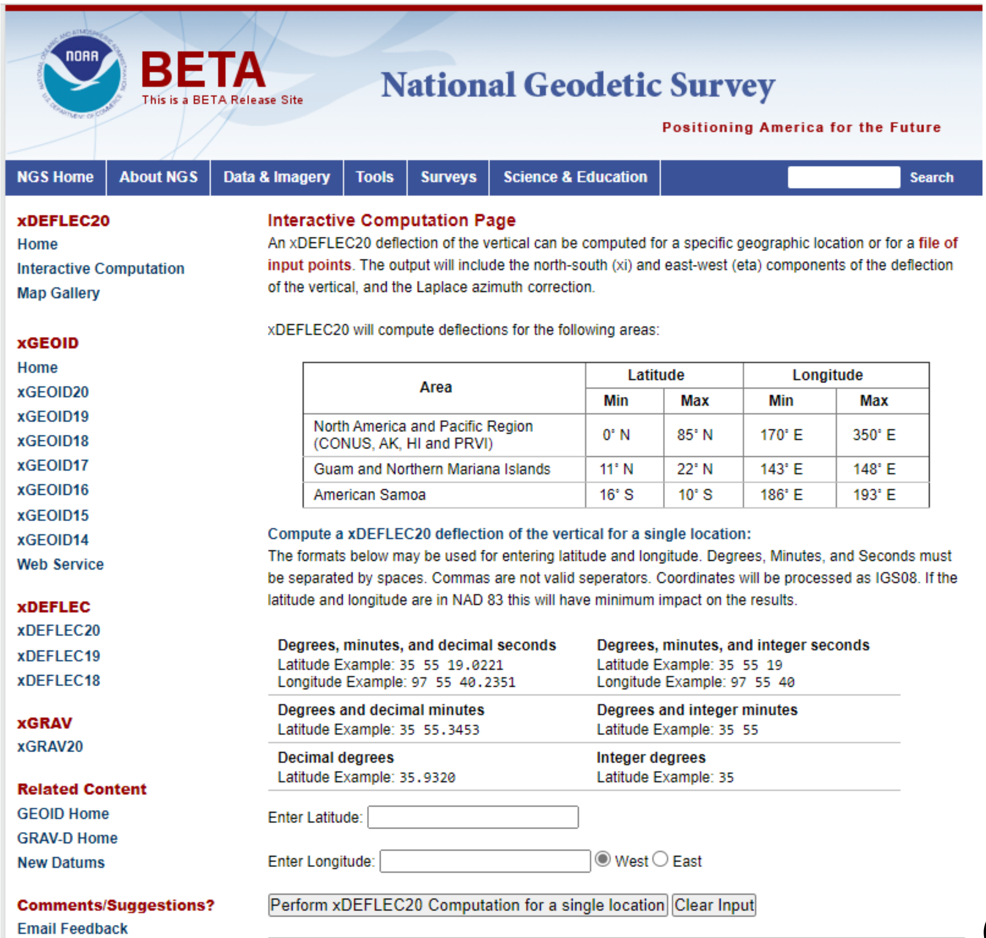
xDeflec and xGrav

Both xDeflec and xGrav were established to produce data for the new vertical datum that will replace NAVD 88 called the North American-Pacific Geopotential Datum of 2022 (NAPGD 2022). The National Geodetic Society has collected and acquired over 10 million terrestrial gravity observations to incorporate with the 100 million GRAV-D airborne gravity measurements. This Dynamic Geopotential Model will be time dependent, due to Continuous Operating Reference Stations (CORS).

NGS started xDeflec to integrate a deflection of the vertical calculation in 2018 to integrate with the xGeoid calculation. Deflection of the vertical is used to measure local deflection of the plumb line to determine geoidal slopes. It is measured in a north/south (Xi) and east/west (Eta) direction.

“The deflection of the vertical is the departure of a plumb bob's actual pointing from the ellipsoidal normal direction. Deflections are used to relate the orientation of a locally leveled instrument, such as a theodolite, to a spatial reference system. Important uses are corrections to zenith distance (vertical angle) measurements, and the conversion between astronomic and ellipsoidal azimuths (the Laplace correction).” (33)

xDeflec18 or xDoV18 models refer to the IGS08 geocentric reference frame. It is computed from the reference ellipsoid to a ground point on the surface of the Earth where a correction for the plumb line is calculated based off gravity anomalies. The xDeflect19 model is used in conjunction with xGeoid19B, which was the predecessor to the most current version xDeflec20 used with xGeoid20B. The National Geodetic Society provides an interactive tool where the user is able to process data in Lat/Long format to determine the deflection at a given coordinate.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xDEFLEC20
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xDEFLEC19
xDEFLEC18

xGRAV
xGRAV20

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GRAV-D Home
New Datums

Comments/Suggestions?
Email Feedback

Interactive Computation Page

An xDEFLEC20 deflection of the vertical can be computed for a specific geographic location or for a file of input points. The output will include the north-south (xi) and east-west (eta) components of the deflection of the vertical, and the Laplace azimuth correction.

xDEFLEC20 will compute deflections for the following areas:

Area	Latitude		Longitude	
	Min	Max	Min	Max
North America and Pacific Region (CONUS, AK, HI and PRVI)	0° N	85° N	170° E	350° E
Guam and Northern Mariana Islands	11° N	22° N	143° E	148° E
American Samoa	16° S	10° S	186° E	193° E

Compute a xDEFLEC20 deflection of the vertical for a single location:

The formats below may be used for entering latitude and longitude. Degrees, Minutes, and Seconds must be separated by spaces. Commas are not valid seperators. Coordinates will be processed as IGS08. If the latitude and longitude are in NAD 83 this will have minimum impact on the results.

Degrees, minutes, and decimal seconds Latitude Example: 35 55 19.0221 Longitude Example: 97 55 40.2351	**Degrees, minutes, and integer seconds** Latitude Example: 35 55 19 Longitude Example: 97 55 40
Degrees and decimal minutes Latitude Example: 35 55.3453	**Degrees and integer minutes** Latitude Example: 35 55
Decimal degrees Latitude Example: 35.9320	**Integer degrees** Latitude Example: 35

Enter Latitude:
Enter Longitude: West East
Perform xDEFLEC20 Computation for a single location | Clear Input

(Image 4.1)

In 2008, NGS implemented the Gravity for Redefinition of the American Vertical Datum (GRAV-D) Project in order to create a highly accurate and organized (easy to follow) gravity model that can achieve accuracy of geoid height down to the centimeter level. The model (GRAV-D) created will replace NAVD 88 and constitute the new vertical height system of the United States. Although not limited to a single country, the cooperation and collaboration of the majority of North and Central America (including the Caribbean) will be necessary to make sure the model can actually serve as the regional vertical datum, as well as, later become linked to the World Height System. There are some challenges and considerations of this large and involved effort.

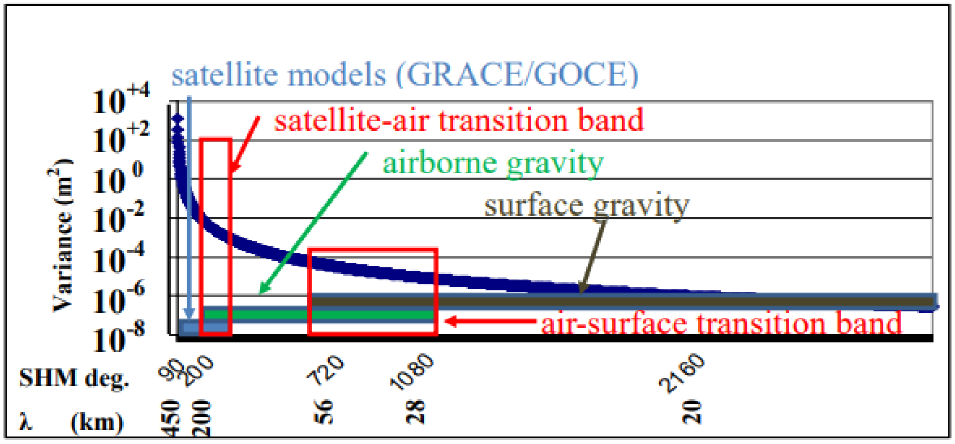
Some of the challenges include the resolution of satellite models, shore gaps in oceanic gravity surveys and biases in the terrestrial gravity surveys. Aerogravity profiles have been collected to improve satellite models, but before this can take place trackwise biases must be eliminated. For removing biases in aerogravity profiles, a simpler approach was taken by blending two reference models (EGM2008 and GOCO03S) as one. Other techniques will be required to achieve a complete resolution of the biases within various surveys and in developmental phases. The purpose in all of this is that aerogravity will find and mitigate NGS surface survey data (lacking of metadata is of major causation and would have otherwise eliminated potential errors). Once corrected for errors and biases: satellite, airborne and terrestrial data will become consistent and capable of producing an uninterrupted gravity field model to serve for a more exact and true vertical control.

Up to this point, geodetic surveys have relied on NAD 83 and NAVD 88. These datum's comprise the NSRS, which is maintained by NGS. Both datum's have strong and demonstrable consistency internally, but the absolute accuracy in question necessitates the replacement of them. One example is the 20-50 cm regional features found in the Pacific Northwest where the zero elevation surface was compared with satellite estimations and a meter difference was discovered.

The plan of resolution (as outlined by the Ten-Year Strategic Plan by NGS in 2013) is to have NAD 83 and NAVD 88 replaced by 2022 with the new geometric and geophysical datum's. The new vertical datum will be achieved by use of a regional geoid height model with continental scale. The models required are developed from global ones that are improved further from regional ones and local surface gravity data. Thus, systematic errors will be addressed and resolved and a centimeter level of accuracy will be possible. By combining GNSS measurement and the geoid height model, the new vertical datum will be established. First, GNSS must find the horizontal coordinates and with this data, the geoid height (at location) can be brought in and utilized from the gridded geoid height model. Then, to know the orthometric height, a linear formula will be applied.

So, what is the case for GRAV-D and why has there been a 10-year plan to replace existing models with it? In the mid 2000's, aerogravity was collected over Alabama and Mississippi in the northern portion of the Gulf of Mexico for a project called Gravity-Lidar Study of 2006 (GLS06). From the aerogravity and surface gravity data, gravity grids were created using data from the Gravity Database at NGS. During the study, a major discrepancy surfaced when comparing airborne and surface gravity data about 200 km from Mobile Bay. The aerogravity profiles observed had major differences when compared to the terrestrial data. Then in 2008, an additional surface gravity survey verified the finding and affirmed the culprit to be the terrestrial gravity data as the problem. The discrepancy resulted in a 10 cm difference in the geoid model making it increasingly inaccurate as a basis of measurement.

The purpose behind the project "is to use the aerogravity to bridge the spectral gap between satellite and surface gravity data." (34) The way this is possible is using the global gravity field, which is represented through SHM (Spherical Harmonic Models). Harmonics demonstrate the power by degree in the photo below.



(Image 4.2)

The longest wavelengths are the satellite models at lower degrees. Most of the power is at the longer wavelengths while also having the lowest degree of harmonics. Surface gravity has the shortest wavelengths while airborne gravity overlaps both areas of the spectrum. Falling off to the right, the variance (power) is higher towards the left side. Satellite data has greater sensitivity to large features within the gravity field and illustrates that longer wavelengths and greater features correlate to lower harmonics on the left.

The significance of the aerogravity surveys are that they guarantee there is signal at wavelengths also observed by satellite gravity missions (i.e. GRACE and GOCE). There is no short wavelength signal within this data because aerogravity is measured at a higher altitude and on a moving platform. Larger degree harmonics actually correlate to smaller scale features that contain less power and the shortest wavelength signal.

In providing long wavelength consistency, regional models will be unified by the satellite model. Satellite data signal will be favored and allow us to ignore inconsistencies of longer wavelength aerogravity. In order to create a reference model that is combined without surface gravity data (to be able to evaluate the data first), the satellite model will be augmented by aerogravity. Once the biases of long to intermediate signals are removed, the normalization of surface data will take place. In doing so, all data will be consistent and then combined into an uninterrupted, cohesive gravity field model that provides a well-defined, highly accurate and precise (repeatable) vertical reference system. This is why the GRAV-D project is a necessity for further advances in geodetic surveying and geodesy and especially so for the replacement of NAVD 88.

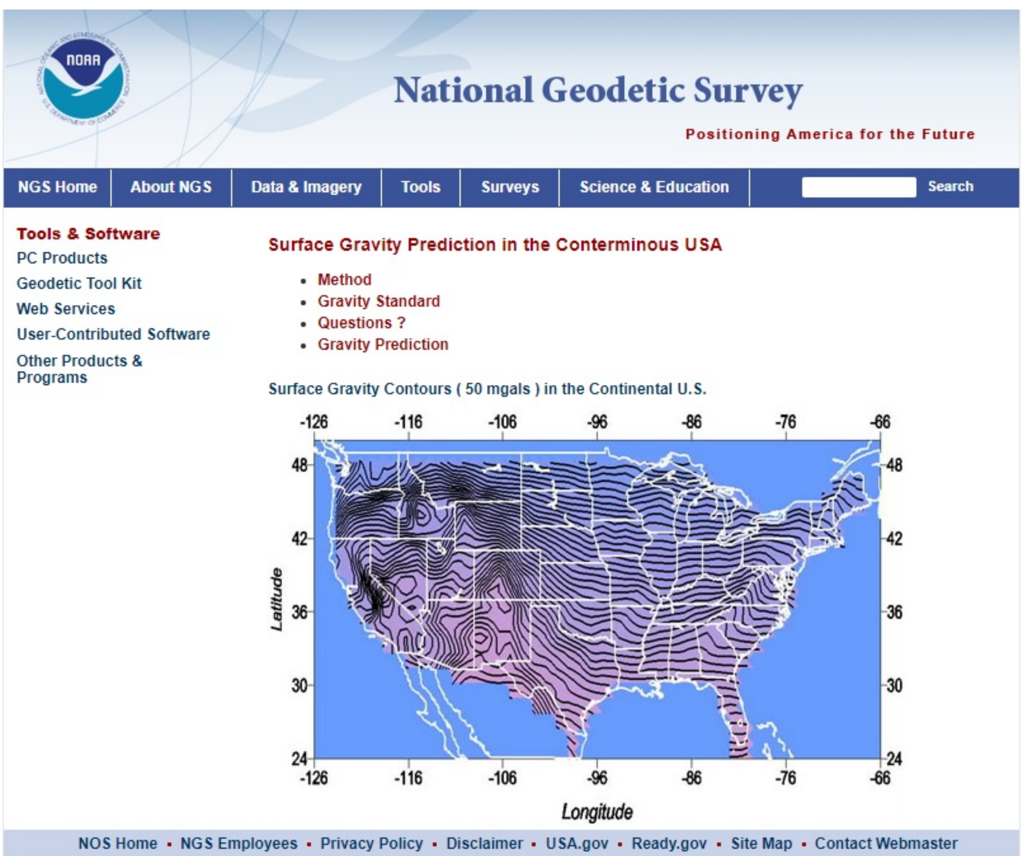
The airborne gravity collection campaign is the most identifiable of the three major components of GRAV-D. This portion is designed to gather observations of the gravity field coastally and achieve complete coverage with techniques that are consistent. The campaign will span the entire continental U.S. and a couple hundred kilometers into Mexico and Canada. The run over is important because it will allow NGS to blend geoid products into bordering and nearby countries. (34)

In deep-water regions, the gravity field is measured through satellite altimetry data. In the case of coastal surveys, they are extended further than the shelf break to allow data to be gathered.

This is because in these regions beyond shelf break, sea surface topography models are better understood. Most importantly, the airborne gravity fills the gap of deep ocean altimetric and terrestrial gravity data. GRAV-D will extend far into the Pacific to Hawaii and Guam and then return eastward into the furthest stretches of the Caribbean and north through Alaska.

"NGS has two existing web-based tools that will predict a full field gravity value at a user provided location: 1) NAVD 88 gravity and 2) the Surface Gravity Prediction Tool. Two different tools that provide almost the same information are needed because they fulfill slightly differently roles. The NAVD 88 gravity data and tool is designed to compute geodetic leveling corrections consistent with the current vertical datum, NAVD 88. It was determined using a gravity model at the time of the NAVD 88 adjustment. Any new or revised gravity values observed since that adjustment have not been incorporated into the NAVD 88 gravity and will have no impact on results.

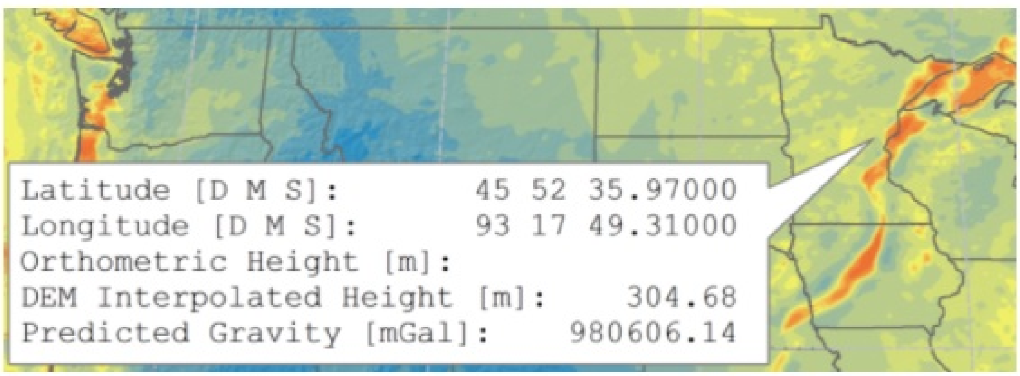
On the other hand, the Surface Gravity Prediction Tool (Fury, 1999) does incorporate new and revised gravity observations into its computations providing a gravity value that is a current reflection of the NGS's Integrated Database (IDB). Additionally, both of these tools are only valid for certain portions of the U.S. and will provide an error if you are outside of the computation region. Furthermore, the Surface Gravity Prediction tool completely fails to provide a value in situations where the uncertainty becomes too large. Both tools have been used for their respective purposes very successfully over the past ~20 years. However, they are both in need of a refresh in order to be coincident with NSRS modernization." (35)



(Image 4.3)

Above, you will see the NGS tool for Surface Gravity Prediction (Image 4.3). From this page, the user then clicks on Gravity Prediction and enters the correct Latitude, Longitude and Height. The software then computes the values and returns that to the user.

“xGrav20 is a companion product derived from the same datasets as those used to construct the xGeoid20B geoid model and represents the gravity value at the surface of the Earth. This provides as a full field gravity value at a user specified location and can be used in geodetic leveling corrections. This is the first iteration and attempt to modernize the existing and old NGS Surface Gravity Prediction Tool. Additionally, as xGrav20 uses a digital elevation model (DEM), the predicted DEM height can also be determined at a user specified location. Users can expect to get back the DEM interpolated height and the predicted gravity at a desired latitude, longitude, and elevation as illustrated in the figure below (note a clickable map is not available with this model).” (36)



(Image 4.4)

NGS 2022 – NSRS Modernization – SPC2022

The Proposed Ten-Year Plan

The NSRS modernization began in 2013 when the National Oceanic and Atmospheric Administration's NGS aimed to “position the U.S. for what is to come”. The ten-year strategic plan was created to achieve this, as well as, to replace the 2008 version of the coordinate system. To achieve modernization, the plan gives special attention to time changes as well as accuracy. Other vetting stakeholder’s include, The American Association for Geodetic Surveying and the National Society of Professional Surveyors. The mission statement is as follows “to define, maintain, and provide access to the National Spatial Reference System (NSRS) to meet the nation’s economic, social, and environmental needs.” (37)

The plan also includes five specific goals (along with sub objectives) the National Geodetic Survey (NGS) wishes to realize through NGS’s 2022 plan. First, operationally focused, NGS wants to assist all users of the NSRS. The goal is to be operationally sound and maintain the work NGS carries out via operational products and activities. Next, use projects as agents of change. This is to overall modernize and improve the NSRS by focusing on the efforts of commencing new, improving existing and closing out unnecessary work. These goals are focused on the system itself and its functions, while the next goals seek to enhance relations with the public employees and ongoing operations. Within this, the objective is to reduce errors (specifically definitional and access-related) down to one centimeter using 15 minutes of GNSS data. The NGS 2022 plan, designed to replace NAD 83 by improving its definitions and services provided for access. NAD 83 has consistently defined itself through relations to the International Terrestrial Reference Frame (ITRF of the International Earth Rotation and Reference System (IERS)). This realization is dependent on analysis of the data from GNSS as well as space geodesy networks. Therefore, NGS is obliged to uphold ITRF. They have done so by beginning, again, the IERS Site Survey program and serving as a coordinator of IGS (International GNSS Service) and center of analysis. (37)

Though the current models of today NAD 83 (2011) and NAVD 88 are still in use, the plan is to migrate to a system that is not based off passive control. One of the main downfalls of the current system is that it is not time dependent. With the establishment of xGeoid, xDeflec and xGrav the modernization of the NSRS will combine multiple datasets in order to establish accurate coordinates with respect to time. Expected to roll out towards the end of 2022, NGS has stated the project is slightly delayed.

The GRAV-D data must be complete in conjunction with Geoid 22 and this is now expected to be late in 2023. As of April 2021, a little over 85 percent of the Grav-D data has been acquired. NGS is still working on tools for the modernization and expanding NADCON and VERTCON. Reference Epoch Coordinates (RECs) are not yet available, so it is likely going to be 2024-2025 until the modernized NSRS is rolled out. NAD 83 wasn't officially adopted until 1986 and NAVD 88 until 1991, so this may be the same type of scenario.

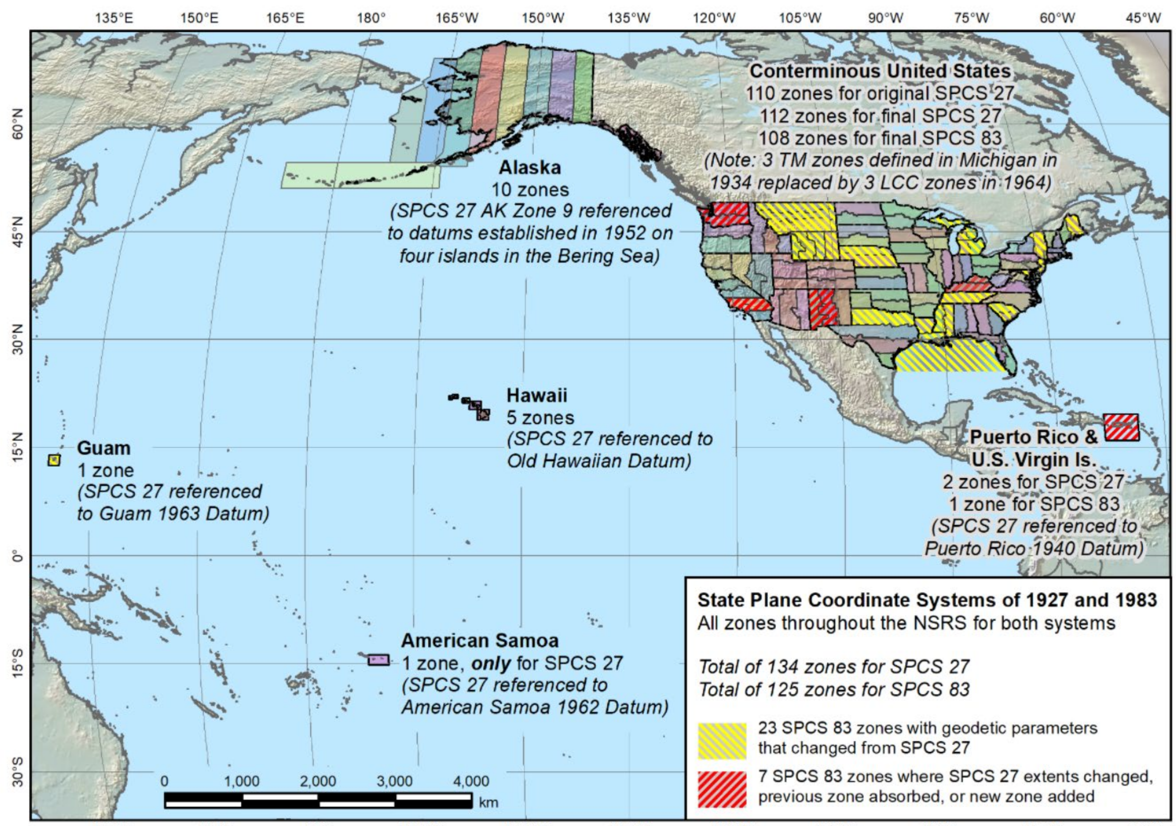
The New Spatial Reference System of 2022 will include the North American Terrestrial Reference Frame of 2022 (NATRF 2022) and the North American-Pacific Geopotential Datum of 2022 (NAPGD 2022) for primary use. The new system will be geocentric and defined by relationships to a global or international ideal frame, primarily accessed through GPS and time dependent. The Pacific Terrestrial Reference Frame of 2022 (PATRF 22), Caribbean Terrestrial Reference Frame of 2022 (CATRF 22) and the Mariana Terrestrial Reference Frame (MATRF 22) will also be implemented.

"The magnitude of change with the new datum's will vary depending on the datum you are using and your geographic location. The new geometric datum will change latitude, longitude, and ellipsoid height between 1 and 4 meters. In the conterminous United States (CONUS), the new vertical datum will change heights on average 50 centimeters, with approximately a 1-meter tilt towards the Pacific Northwest." (38)

Once implemented, the four plate-fixed Terrestrial frames will be able to generate a time dependent Cartesian coordinate that relates to the International Terrestrial Reference Frame of

2020 (ITRF 2020). “The relative relationship will rely on a plate rotation model for each tectonic plate associated with each frame. This relationship will rely on rotations about the three ITRF axes (called Euler pole parameters, or EPPs), and be codified in a model called EPP 2022. Such time dependent coordinates will exhibit coordinate stability in areas of the continent where motion of the tectonic plate is fully characterized by plate rotation. All remaining velocities (including horizontal motions induced directly or indirectly by adjoining tectonic plates, horizontal motions induced by glacial isostatic adjustment, other horizontal motions and all vertical motions in their entirety) will be captured by a model, tentatively called an Intra-Frame Velocity Model (IFVM) and tentatively named IFVM 2022.” (39)

As of March 31st of 2021, NGS has received designs for 28 states including more than 800 low-distortion projection zones. Once NGS has reviewed, they will make the final determination on the zone designations. Each state is not required to submit a design. Below is an image of the original 134 zones for the State Plane Coordinate System of 1927 (SPCS 27) and the 125 zones for State Plane Coordinate System of 1983 (SPCS 83) (Image 5.1).



(Image 5.1)

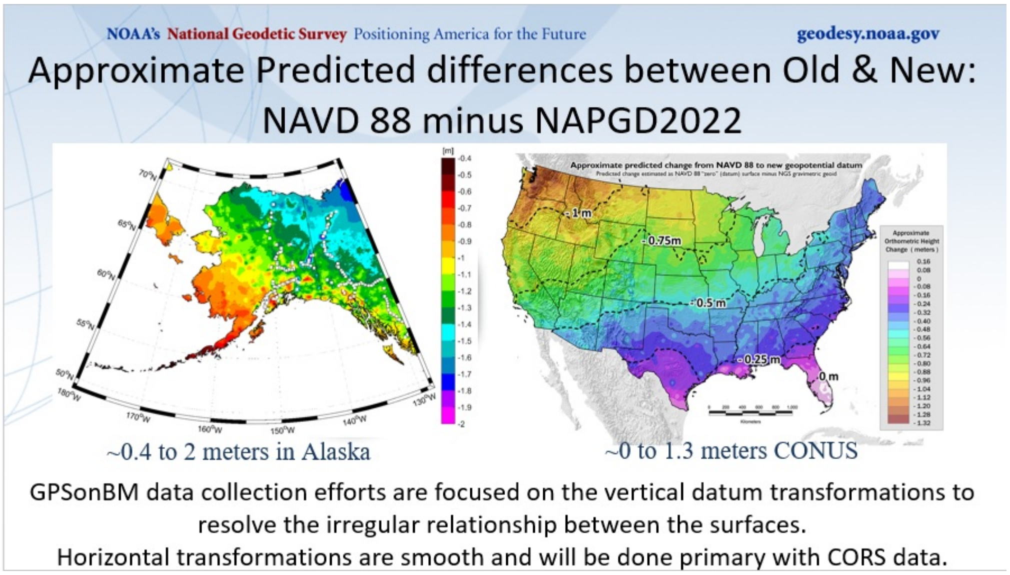
One new element to the State Plane Coordinate System of 2022 will be the addition of Low Distortion Projections (LDP’s). “The projection may cover a county or city, a section or original grant, a neighborhood or even various elevation zones of any of the above. The projection may look to have North be North along some particular meridian, or be customized to fit an existing bearing in an existing coordinate system that was originally determined by less precise means (such as from a compass). The "plus" to all of this is a system that gives coordinate inverses substantially equivalent to distances measured along the ground, and is related to North or very nearly North, and that can be used in an RTK controller, GNSS post processing software or mapping software to directly convert from those coordinates to latitude and longitude or any other projection (such as State Plane or UTM) at the touch of a button.” (40)

Another major change slated for 2022 is the definition of the foot. The “U.S. survey foot” which is 2 parts per million larger, will no longer be accepted. The reason for changing the measurement is to standardize the foot and to establish a fixed value. The Federal Register was the organization that initially allowed for the temporary use of the U.S. survey foot for geodetic surveying in 1959. Although, it was initially a direct correlation to the meter fixed at 1200/3937. The new accepted conversion value for the foot will be 0.3048 meters. The new value will override any state statute because will be mandated by the National Institute of Standards and Technology (NIST).

“Although the use of the “U.S. survey foot” was intended to be an interim measure, its use continues to be prevalent in land surveying and mapping in much of the U.S. Of the 50 U.S. jurisdictions that have legislated SPCS 83 (48 States plus Puerto Rico and Guam), the “U.S. survey foot” has been specified for SPCS 83 in 40 States, either through statute (28 States) or Federal Register notices (12 States). Six States have adopted the “international foot” for SPCS 83, while two States (plus Puerto Rico and Guam) have not formally designated the type of foot to be used. It is important to note that State legislation and Federal Register notices regarding the “U.S. survey foot” are specifically associated with SPCS 83, and therefore are not applicable to the NSRS Modernization in 2022.” (41)

The National Geodetic Society is also implementing a GPS on Benchmarks project and building a transformation tool called NCAT. Users from different locations are asked to submit GPS data in order to increase the accuracy level of the North American-Pacific Geopotential Datum of 2022 (NAPGD 2022). This will provide a tool that enables mapping grade conversions from previous datum’s to NAPGD 2022 once it is officially adopted by the NGS.

Below, you will see the approximate elevation changes from NAVD 88 to the New NAPGD 2022 (Image 5.2).

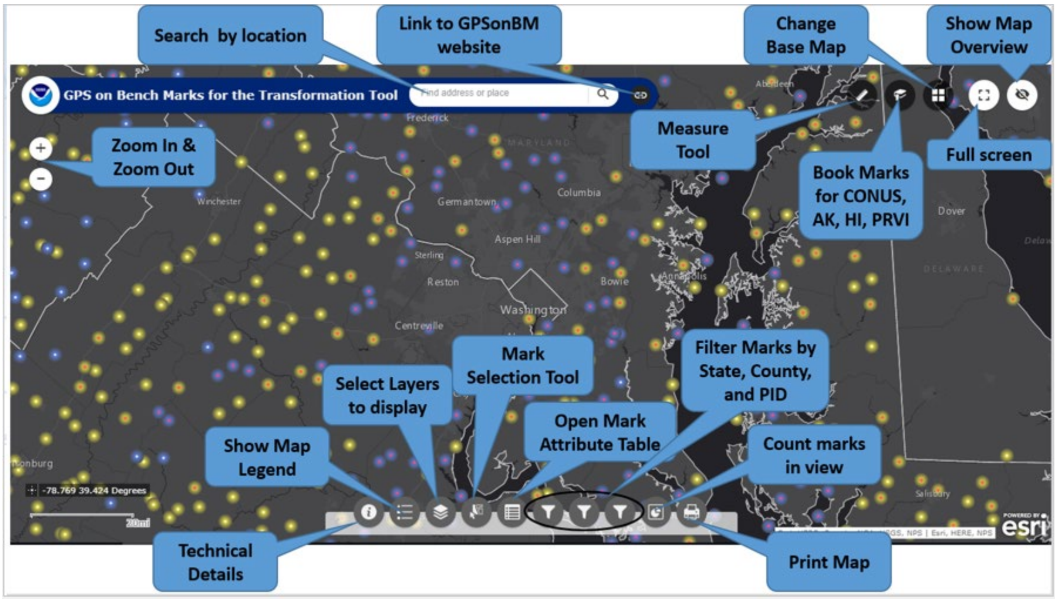


(Image 5.2)

The goals for the 2022 Transformation Tool Campaign (42) are:

- NGS will make a national scale, mapping grade transformation tool with the data we have in the NGS Database or Shared through OPUS
- To produce transformation results with an reasonable amount of uncertainty, NGS has a goal of GPSonBM data at 10 km spacing
- We must interpolate over areas with data gaps
- Uncertainties in the transformed coordinates will grow larger as the distance from a GPSonBM data point increases
- Opportunity exists to densify local areas with data at up to 2 km spacing to increase accuracy and better resolve complex areas with topographic relief

NGS is looking for observations to be submitted by December 31st, 2021. Each GPS session should be at least a four hour observation and within 3 years from the requested submittal date. RTK or Real Time Kinematics observations will soon be accepted to process Hybrid Survey Networks. The image below shows the different functionalities of the Transformation Tool (Image 5.3).



(Image 5.3)

In conclusion, the National Geodetic Society has put in a great deal of work to modernize the National Spatial Reference System. This will change the way geodesists, surveyors and engineers work with data. This revolutionary system will be in place for a long time and like anything new, it will take time for the user to adapt.

The Continuous Operating Reference Systems (CORS) is changing the way we interact with mapping grade data. Everything from the definition of the foot is being modernized. NGS missed out on that opportunity the last time we updated datum's.

"The NOAA Continuously Operating Reference Stations (CORS) Network (NCN), managed by NOAA/National Geodetic Survey, provide Global Navigation Satellite System (GNSS) data, supporting three dimensional positioning, meteorology, space weather, and geophysical applications throughout the United States.

Surveyors, GIS users, engineers, scientists, and other people who collect GPS/GNSS data can use NCN data, acquired at fiducial geodetic control stations, to improve the precision of their positions, and align their work within the National Spatial Reference System (NSRS). NCN enhanced post-processed coordinate accuracies can approach a few centimeters, both horizontally and vertically." (43)

It is an interesting time to be involved with the mapping profession as things are changing rapidly. The overwhelming majority of geodesists, surveyors, engineers and mapping technicians have never gone through this type of change. In the upcoming years, we will have a large learning curve in order to measure the Earth.

Though the projects are delayed, it looks like NGS is on the right track to finish and implement the system within 4 years. Converting data from a passive system to a time based system will bring its own unique challenges. We can expect several new state statutes to be written based off the work done by the supporting agencies. We can expect the legislation for the abandonment of the U.S. Survey Foot in 2022 and the rest of the changes to follow shortly thereafter.

New State Plane Coordinate Systems will be defined in state legislature with new zones. The addition of LDP's will allow for a higher accuracy of surveying in certain areas. Once the system is established, mapping professionals will be quick to adapt. One has to think that NGS really pushed hard to modernize the mapping industry. This was a tall task to take on with tight deadlines. 2021 will be a year where they are trying to fix areas to coincide with other datasets.

Living maps are a thing of the future and NGS had done a great job paving the way to establish a system of measurement that coincides with real time data. The last 70-80 years of technology have paved the way for the future of mapping. We are living in an age where smart cities and smart cars will use this technology and it will continue to evolve.

"It is paradoxical, yet true, to say, that the more we know, the more ignorant we become in the absolute sense, for it is only through enlightenment that we become conscious of our limitations. Precisely one of the most gratifying results of intellectual evolution is the continuous opening up of new and greater prospects." Nikola Tesla

About The Author

Robert T Loane III, is a Professional Land Surveyor currently located in the Denver, Colorado area. Robert has around sixteen years of various experience in the Surveying and Mapping industry. He has worked on high profile construction projects across the United States from Florida to Alaska, most notable the Port of Miami Tunnel Project and the Urenco, USA Uranium Enrichment Facility. Robert has been featured in both "the American Surveyor" and "POB" magazines for projects throughout the United States. He was a guest on NSPS "Surveyor Says" Podcast and The Geoholic's Podcast. He has completed his Bachelors of Science in Geomatics Engineering from Florida Atlantic University. Robert has also earned his graduate certificate in Geospatial Analysis and his Master's Degree from the University of Florida. Robert currently holds the role of Senior Survey Project Manager at Tri-State Generation and Transmission. He handles the surveying responsibilities in New Mexico, Wyoming, and Colorado and teaches Land Surveying and Civil Engineering at the University of Wyoming.

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