
Introduction and Overview of Geodesy and GNSS***Introduction***

Topics 1 and 2 are intended to give the student a fundamental understanding of the concepts related to Geodesy and Global Navigation Satellite Systems (GNSS) including the Global Positioning System (GPS). They will cover historical concepts as well as concepts that are being used by geodetic surveyors and scientists today. They will also cover information that is specific to geodetic surveying in California. The successful student will be able to apply the concepts to his/her daily surveying tasks.

There are two texts for the geodesy segment are, Basic Geodesy, An introduction to the history and concepts of modern geodesy without mathematics by J.R. Smith, and Land Surveyor Reference Manual, (Third Edition) by Andrew L. Harbin. “Basic Geodesy” uses an *easy to read and understand* approach to this subject. The information related to the GNSS segment will be contained in the lesson text. Additional sources of information will be cited/discussed for the student who chooses to do further investigation of these subjects, they are not required reading.

Expectations

The student is expected to read and understand all of the reference materials and the lesson text for each lesson. The student will also be expected to answer the questions and work the problems associated with each lesson. Both of the above are essential for a full understanding of the material.

Additionally, the student is expected to be able to use a scientific calculator that will perform surveying calculations. Mathematical processes will be presented in general terms followed by an example. The student will then be given problems to solve/calculate. It is expected that all problems be successfully worked. All of the answers will be in the reference materials or the lesson text.

Overview of Geodesy

Geodesy as a discipline has been around for centuries. Today its concepts are utilized by mathematicians, physicists, scientists, engineers, planners, and surveyors to name a few. The disciplines that these encompass are Geophysics, Space Science, Astronomy, Oceanography,

Atmospheric Science, Geology, and Surveying. Some of the concepts are utilized by those disciplines to locate points above, on, and below the surface of the earth in three-dimensional coordinate systems. Other concepts are utilized to determine the size and shape of the earth as well as the earth's gravitational field. So, what is the definition of geodesy? Definitions of geodesy can range from one sentence to several paragraphs. Four common definitions for geodesy are:

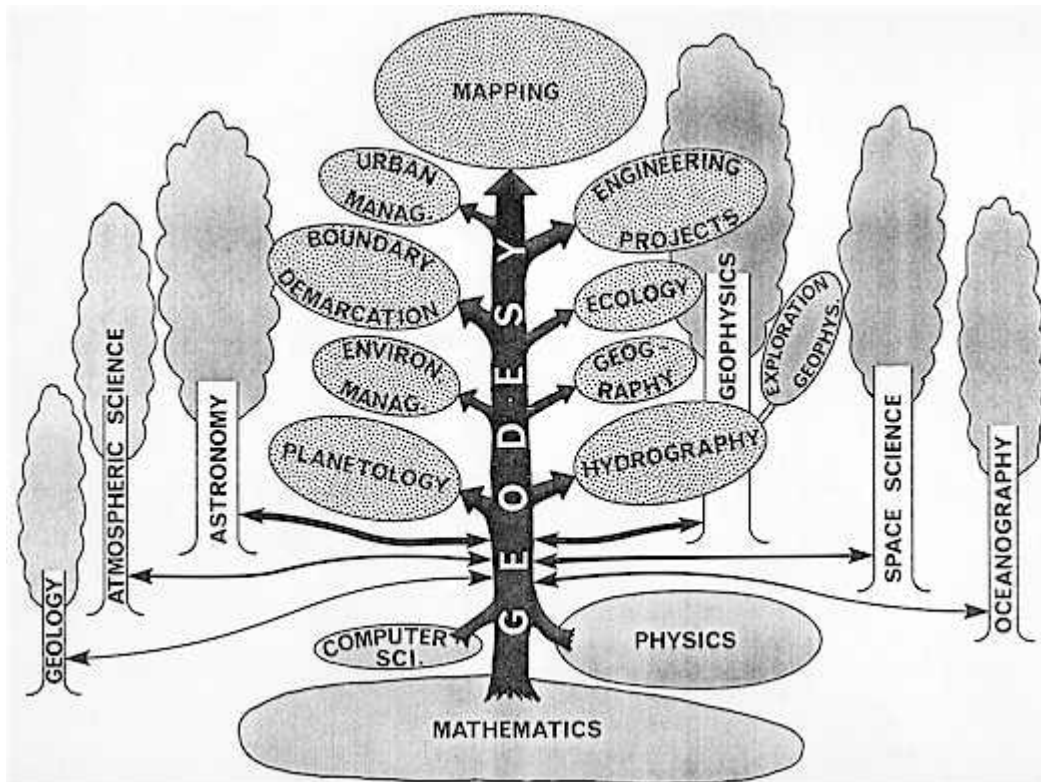
Geodesy is the discipline that deals with the measurement and representation of the earth and other celestial bodies and their respective gravity fields, in a three-dimensional time varying space.

Geodesy is the geologic science of the size and shape of the earth.

Geodesy is the branch of geology that studies the shape of the earth and the determination of the exact position of geographical points.

Geodesy is a branch of applied mathematics which determines by observation and measurements the exact positions of points and the figures and areas of large portions of the earth's surface, the shape and size of the earth, and the variations of terrestrial gravity.

The following picture shows the relationship of Geodesy to other disciplines:



So, geodesy is mainly concerned with positions of points etc. with respect to coordinate systems while utilizing mathematical models representing the earth. The main products produced from geodesy concepts are in the area of mapping. This, of course, is what surveyors do on a daily basis – make maps. They make these maps from geodetic control networks established upon geodesy concepts. Some of the products produced using geodesy concepts are:

Mapping: It is well understood that there is a need for a network of appropriately distributed points (geodetic control) of known horizontal and vertical positions for the production of maps ranging from small-scale maps of entire countries to large-scale maps used by municipalities. The establishment of this control network is clearly an important geodesy (geodetic) task.

Urban Management: In the urban environment, the locations of man's creations, such as underground utilities, must be defined and documented for future reference.

Engineering projects: During the building of large structures, such as dams, bridges, highways, and factories, it is necessary to lay out the various components of these structures in

predetermined locations. For this purpose, coordinates of one kind or another are used, so the availability of control points is naturally desirable. As well, it is often necessary to know the movements of the ground and water levels prior to, during, and after the construction. In the case of dams, water tunnels, irrigation projects and the like, the exact shape of the equipotential surfaces of the gravity field (geoid) should be known. The determination of the movements and the shape of the equipotential surfaces are also geodetic undertakings.

Boundary demarcation: The rigorous definition of international and intranational (provincial or state) boundaries is of paramount importance. Emphasis has also recently been placed on speedy and accurate description of oil and gas leases, even in such remote and inhospitable parts of the world as the Arctic, the North Sea and various continental shelves. The positioning and staking out of these boundaries is most economically done by relating them to a framework of points with known horizontal coordinates - the geodetic network.

Ecology: In the past few decades, society has recognized that it is necessary to study the effects of human actions on the environment. One such effect is structural and surface movement of the ground caused by the removal of underground resources (water, oil, minerals, etc.), and/or subsurface disposal of wastes. The detection and monitoring of these movements is a geodesy problem.

Environmental management: It has also been recognized that the establishment of environmental data banks can serve as the basis of integrated information systems. The location of transportation facilities, community and social services, land titles extracts, tax assessment data, zoning and land use controls, and population statistics, are most efficiently based on parcels uniquely defined in terms of coordinates. These systems work best when the coordinates be referred to a geodetic network.

Geography: All the positional information needed in geography is provided by geodesy. Even though the level of accuracy for positional and geometrical information used by geographers is generally much lower than that needed in the other fields described above, often this information is a global character that only geodesy can satisfy.

Planetology: It can be argued that this is a part of either astronomy or geophysics. Be that as it may, planetology uses methods for studying the geometry, gravity fields, and deformation of planets that are identical with the terrestrial methods used in geodesy. Thus, practically all of geodesy is applicable to planetology. Because of this special affinity between planetology and geodesy, some geodesists regard the determination of the shape and size of planets and their gravity fields as part of geodesy.

Hydrography: The science of hydrography deals with the measurement and description of the physical features of the oceans, rivers, and lakes, together with their adjoining areas. Particular emphasis is placed on control and utilization, both in terms of infrastructure improvements and resource management/exploitation. Surveyors are becoming more involved in this field, particularly marine (near-shore and off-shore) surveying. Hydrography frequently involves large areas necessitating the use of geodetic concepts and methods.

The main geodesy technique used by surveyors is the location of objects via latitudes, longitudes, and ellipsoid heights; followed by a projection of these values into a plane coordinate system and an elevation. This is accomplished by using a reference ellipsoid and a geoid, represented by mathematical models. These mathematical models, along with geodetic surveying techniques, enable the professional to place appropriate coordinates and elevations on the objects to be represented on a map or other geodesy related product.

Utilizing geodesy techniques enables professionals, including surveyors, to assure that a project has a consistent coordinate system from the planning stage through the design phase and ultimately through the construction phase. As a matter of fact, it is absolutely imperative that a coordinate system for a project be consistent. If Geodesy concepts are not properly applied to these projects, disastrous results can happen.

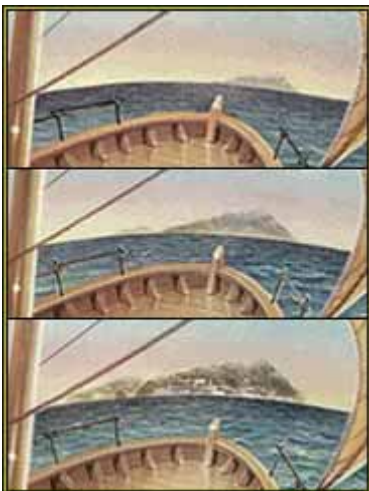
Possible Consequences of Using Inconsistent Coordinate Systems



To ensure that the student is not involved in a project like the one above, subsequent lessons in this period will discuss, at length, fundamental Geodesy concepts, reference systems, transformations and projections between reference frames, state plane coordinates, and laws related to geodesy that can then be applied to any project.

History of Geodesy

Throughout history parts of many cultures believed the world was flat. Of course it's flat! How could a non-flat surface retain the water in lakes, seas, and oceans? Also, if it were not flat, wouldn't we fall off? In most instances, it was the religious and political authorities that upheld the idea of a flat earth. This happened well into the sixth century.



Others, however, realized that the earth was not flat. Fisherman, or those watching marine vessels, would see that objects would disappear or appear on the horizon with the top of the object to be the last to leave sight or the first to become visible. This is illustrated by the picture to the left from the National Geographic Society.

Additionally, farmers working in their fields noticed the changing lengths of daylight and the maximum height of the sun throughout the year, leading them to the conclusion that the earth is not flat.

Early Greek mathematicians and philosophers such as Homer, Plato, and Pythagoras had many different ideas as to the actual shape of the earth. Some thought it was flat, while others (believe it or not) argued that the earth was actually rectangular in shape. By the time of Pythagoras (circa 580 – 500 B.C.) most mathematicians considered the earth to be spherical in shape, partly because “the sphere” was considered by philosophers to be the perfect regular solid. This idea was supported by Aristotle 100 years later.

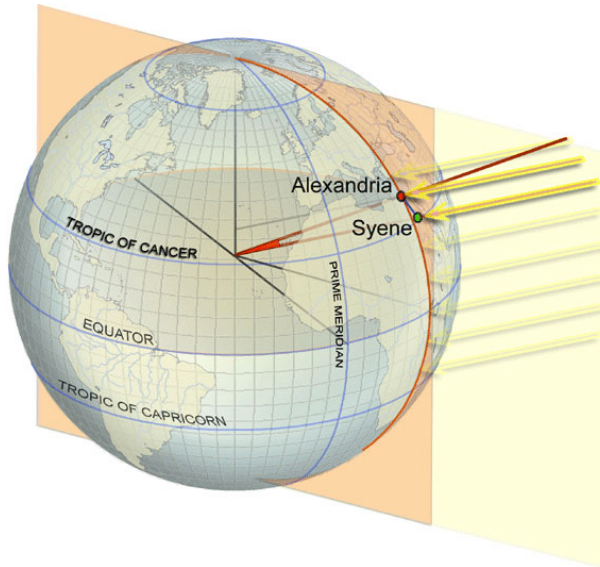
Aristotle determined the circumference of the earth to be 400,000 stades (as in stadia). Nobody knows how he came up with that figure. A century later Archimedes claimed it to be 300,000 stades without stating how he came up with that figure.



Well, how do you prove the earth is round in ancient times as well as to measure its size? Eratosthenes (pronounced like "Era tossed the knees") was a librarian in ancient Egypt, noticed that on the longest day of the year (the summer solstice) when the sun reached it's zenith in the sky, a stick placed straight up and down in the sand did not cast a shadow. He also looked down into a dry well, noticing that the midday sun shone straight to the bottom and the walls of the well were in sunlight. Eratosthenes reasoned that the sun must be directly overhead.

He then decided to conduct an experiment where he would place a second stick into the sand in a different location and see if it would cast a shadow. If the second stick cast a shadow, then the earth could not be flat (as some at the time presumed) but must be curved (spherical). Eratosthenes then applied what he knew about mathematics to determine the earth's size. He knew that if he could measure the distance between the two sticks as well as the length of the shadow cast at the second stick, he could calculate the size of the earth.

So Eratosthenes, who lived in Syene (now Answan) raced off on his camel to Alexandria,



some 500 miles away, placed a stick in the ground and measured the shadow. From how far his camel could travel in a day and the measurement of the shadow in Alexandria, he determined the circumference of the earth to be 25,000 miles. The process that Eratosthenes used was based on calculating the difference in the vertical plum lines at Alexandria and Syene, which would be the same

angle subtended at the center of the earth by those two plum lines (see illustration). Coupled with the distance he calculated from his camel ride between Alexandria and Syene, he derived the circumferential distance of Earth at its equator. Recent research indicates that Eratosthenes' had a "calibration error" in the length of his camel's pace. The currently accepted circumference is 24,901 miles. None the less, the accuracy of Eratosthenes calculations are amazing.

A century later, another Greek – Posidonius – made a separate calculation of the size of the earth. He noted that the star Canopus was hidden from view in most parts of Greece, but that it was just visible on the horizon at Rhodes. Posidonius then measured the elevation of Canopus at Alexandria. He then assumed the distance from Alexandria to Rhodes to be 500 miles, derived from mariner's estimates (as the two cities are separated by water). Using this data, he computed the circumference of the earth as 24,000 miles. His calculations had two (compensating) errors; the angular elevation of Canopus, and the distance between Rhodes and Alexandria. But, he achieved a fairly accurate result.

The Chinese were also interested in the size and shape of the earth. In the 8th century A.D. they based their understanding of the size of the earth on the ideas by I-Hsing, who was a Buddhist monk and a famous mathematician and astronomer. He was charged with conducting measurements that were variations on the same theme used by Eratosthenes. His determination of the circumference was basically consistent with Eratosthenes.

Another Alexandrian, Ptolemy (A.D. 100-178), utilized the value 18,000 miles for the circumference of the earth to create his maps of the world. The maps of Ptolemy strongly influenced the cartographers of the middle ages. Some think that Columbus, using Ptolemy style maps, was led to believe that Asia was only 3 or 4 thousand miles west of Europe. Another explanation is that Columbus used Italian miles instead of Arab miles in his calculations. It was not until the 15th century, when the Flemish mapmaker Mercator made successive reductions in the size of the Mediterranean Sea as well as Europe, that Europeans had a more realistic value for Earth's circumference. Mercator's changes had the effect of increasing the size of the earth.

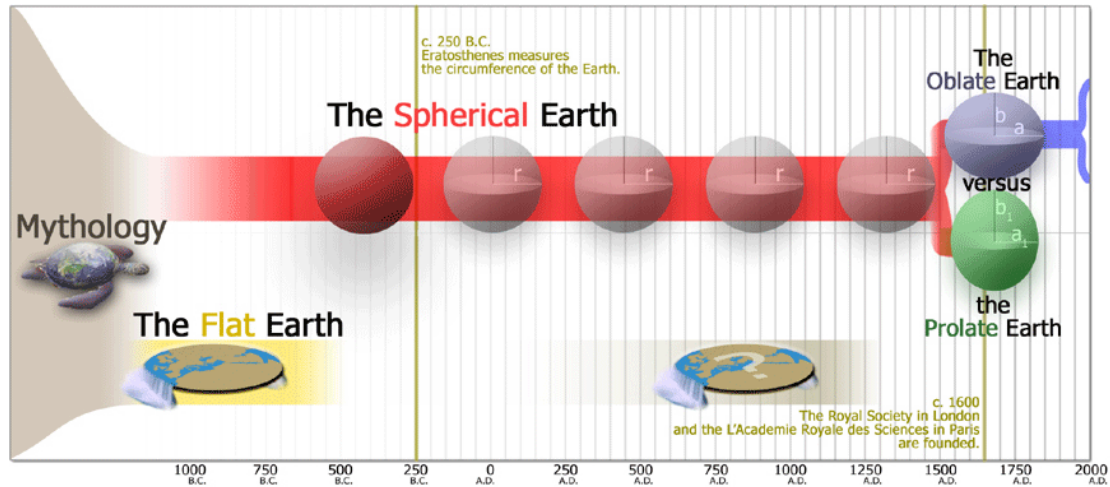
With advances in most aspects of science during the 17th century (including the telescope, logarithmic tables, and triangulation) measurements of an arc of the earth were easier to make. Jean Picard (1620 – 1682) a French astronomer, measured a base line by the aid of wooden rods. Using a telescope to measure his angles, and logarithms, he calculated the dimensions of the earth. Gian Domenico Cassini (1620 – 1712) an Italian-born French astronomer, later continued Picard's work. When Cassini completed his measurements and calculations he found that the length of one degree of longitude in the northern part of his work was shorter than that in the southern part. Assuming that his measurements were correct, this unexpected result could have been caused only by an “egg-shaped earth”.

At the same time, the Royal society in London was also making measurements to calculate one degree of arc in different parts of the world. Their measurements, along with the theories of Sir Isaac Newton, suggested that the earth was flattened at the poles. This was in direct contradiction to the “egg-shaped earth” championed by Cassini and L'Academie Royale des Sciences (the French Academy of Sciences) in Paris'.

To settle the controversy, the French Academy of Sciences sent a geodetic expedition to Peru in 1735. They measured the length of a meridian degree close to the equator, and another team made a similar measurement in Lapland, near the Arctic Circle. The measurements conclusively proved the earth to be flattened at the poles, as Newton had theorized. The joke of the day was that the French sent people half way around the world to prove what Newton knew sitting in his study.

The “egg-shaped earth” (flattened at the equator) is known as a prolate earth. An earth flattened at the poles, is known as an oblate earth. The following illustration from the National

Oceanic and Atmospheric Administration shows the development of concepts of the shape of the earth.



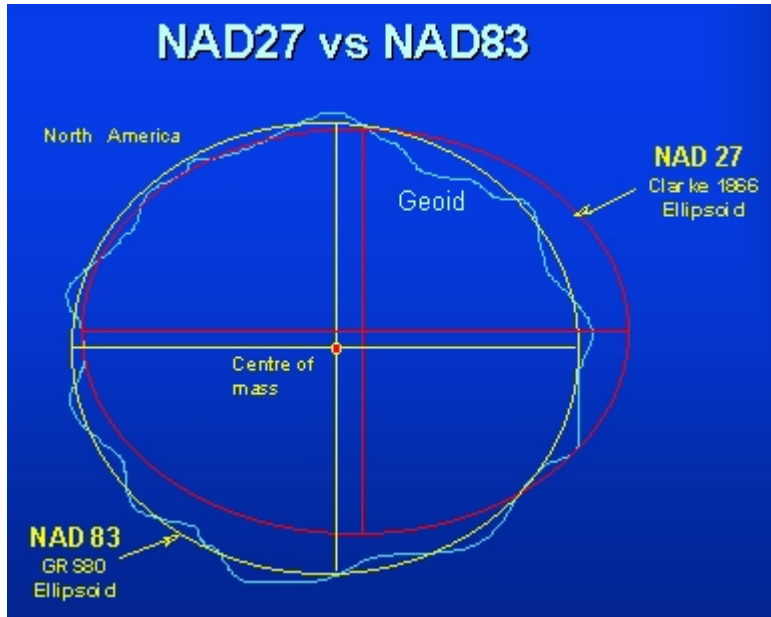
Partly from the surveys performed by the French and English, as well as Newton's theories, it was realized that the surface of the earth was irregular and this affected Earth's gravitation field. In order to measure the earth and avoid the problems associated with the irregularities and the variation in Earth's gravitation field, geodesists have made use of mathematical models known as ellipsoids and geoids.

Ellipsoids are models that are created by rotating an ellipse about its shorter axis. Because Earth is oblate, a good ellipsoid (that will best represent it) will rotate on its polar axis. A good fitting ellipsoid model of the earth makes it easy to locate objects (longitudinally and latitudinally) with respect to a consistent reference frame, called a horizontal datum.

The Geoid, on the other hand, is a gravitational equipotential surface that represents mean sea level throughout the world. Its mathematical representation is an undulating surface since mean sea level changes due to gravitational variations. The geoid is utilized to locate points vertically with respect to a consistent reference frame, called a vertical datum.

The United States has made use of several different ellipsoids in the last 150 years. Clarke's Spheroid of 1866, introduced by the British geodesist Alexander Ross Clarke, was the basis for the national horizontal datum known as the North American Datum of 1927 (NAD27).

The current national horizontal datum, known as the North American Datum of 1983 (NAD83), is based on the Geodetic Reference System of 1980 (GRS80). The following illustration depicts the relationship of Earth to NAD27, NAD83 and the geoid.

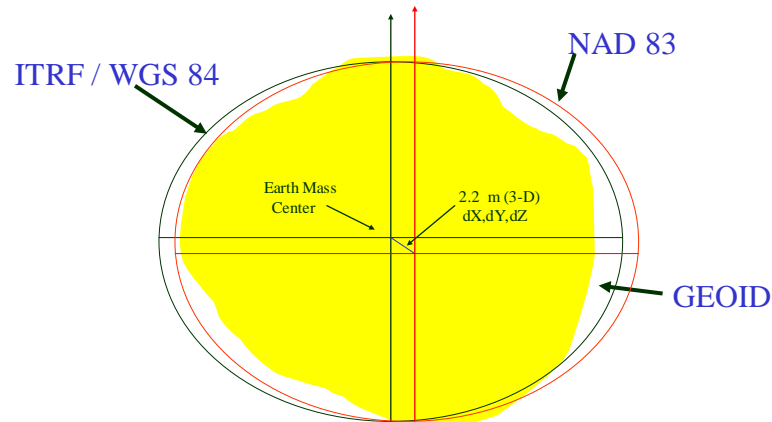


As you can see from the illustration, Clarke's Spheroid of 1866 represented the earth well in North America, but not very well anywhere else. The GRS80, however, works well for the whole world. You can also see the undulating surface of the geoid.

The International Terrestrial Frame (ITRF) is generally accepted as the best current representation of Earth. It is a model that was created and approved by geodesists the world over. The model is continually reviewed and revised based on current scientific understanding and new measurement data. The World Geodetic system of 1984 ellipsoid (the basis of our GPS system) is closely related to the ITRF. The following illustration, from the National Geodetic Survey, shows the relationship of NAD83 (GRS80) to WGS84 as well as the geoid.



NAD 83 and ITRF / WGS 84

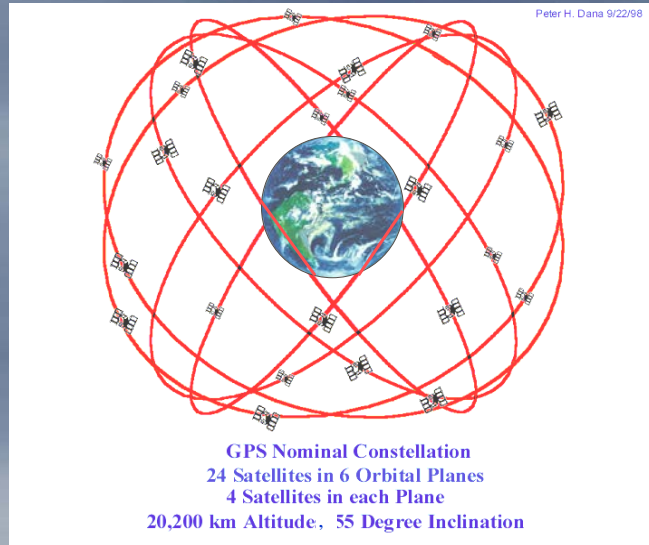
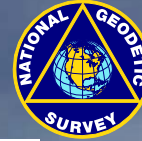


So, this is just a brief history of geodesy and can be pursued further by the student in such texts as: “From Plane to Spheroid-Determining the Figure of the Earth from 3000 B.C. to the 18th Century Lapland and Peruvian Survey Expeditions” by James R. Smith, “Geodesy: An Introduction” by Torge, and the text, “Introduction to Geodesy - The History and Concepts of Modern Geodesy” also by James R. Smith.

Overview of Global Navigation Satellite Systems (GNSS)

While the field of Geodesy has been around for centuries, Global Navigation Satellite Systems are a relatively new technology, having been around in concept-form since the early 1970's. Fundamentally, GNSS (including GPS) are based on Geodesy concepts. The GNSS satellites are in orbits around the earth that are related to the geodesy model (ellipsoid) known as the World Geodetic System of 1984 (WGS84). While in orbit, they send out signals that can be utilized by receptors that are able to detect and receive them. The following illustration from the National Geodetic Survey depicts the GPS satellite constellation.

Global Positioning System GPS



So, what good is it to have a bunch of satellites orbiting around the world sending out signals? Well, the reception of the signals from a GNSS answers the questions, “What time is it, what position is it, and what velocity is it?”, anywhere in the world at any time – in a quick and inexpensive manner. The answers to these questions can be utilized by many applications, producing numerous navigational products.

The original application of the GNSS technology was for military purposes. This was most evident during the Gulf war in the early 1990’s when it was deployed for target location and weapons navigation purposes. Almost nightly during the war, the news stations would show images of GPS guided missiles hitting their targets with remarkable accuracy. It was also used during that conflict to locate and identify friendly versus non-friendly forces.

While military applications were the primary reason the Department of Defense spent \$13 billion on the satellite system, the GPS signals are available to anyone worldwide – free of charge. This means that anyone clever enough to take advantage of the signals and creative enough to come up with an application that uses the resultant data, has a powerful tool at their disposal. This is exactly what happened with civilian industry. Some of the civilian applications utilizing data produced from GNSS signals include:

Geographic Information Systems (GIS): A computer system for capturing, storing, checking, integrating, manipulating, analyzing and displaying data related to positions on Earth's surface. Typically, a GIS is used for handling maps of one kind or another. These might be represented as several different layers where each layer holds data about a particular kind of feature (e.g. roads, hospitals, rivers, etc.). Each feature is linked to a position on the graphical image of a map. GIS's are used for town planning, local authority and public utility management, environmental, resource management, engineering, business, marketing, and distribution to name but a few. GNSS data is used prominently in most GIS's, in fact, without the efficiency of data gathering that GPS provides, GIS would be not be economical possible.

Navigation: Navigation is the guidance of airplanes, marine vessels, and other motorized vehicles such as trucks, buses, and passenger vehicles. GNSS technology has become the system of choice by the airline, shipping, trucking, and other industries to provide navigational information to the operator as well as to the people who are tracking them.

Geodetic Control: Specific points on the earth that provide horizontal or vertical control for scientific, engineering, and planning purposes are known as geodetic control. They form a network of monumented stations that are precisely measured in accordance with standard procedures. Today, the main method of establishing geodetic control utilizes GNSS techniques.

Topographic Maps: A topographic map is a visual display of the relief features on the surface of the earth, usually by means of contour lines to show changes in elevation. GNSS collected data often times is merged with terrestrial data in the production of these maps. The trend is an increasing reliance on GNSS data gathering due to its lower cost.

Location of Fixed Works: Knowing the horizontal and vertical position of fixed features provides useful tools for their maintenance, operation, and management. The location of fixed works with respect to a reference frame enables the professional to evaluate their location (horizontally and vertically), particularly their relationship to other features – both nearby and far away.

Construction Layout: A coherent horizontal and vertical reference framework is the basis of modern community and engineering design. Surveyors have used GNSS in the

construction layout of dams, bridges, roadways, subdivisions, and commercial buildings for several years now. There is a growing trend to use the technology to guide (control) the equipment itself.

Asset Management: The process whereby a large organization collects and maintains a comprehensive list of the items it owns such as hardware and software. This data is used in connection with the financial aspects of ownership such as calculating the total cost of ownership, depreciation, licensing, maintenance, and insurance. The information related to the location and/or movement of assets often times is achieved by the use of a GNSS.

Emergency services: With the advent of cell phones, the 911 emergency response system had difficulties locating someone in need of help who was using a cell phone. This was because a landline telephone has an address associated with it, while a cell phone can be almost anywhere. Currently, cell phones are being equipped with GNSS technology to aid 911 operators in locating the caller and dispatching emergency services.

Large-scale disasters, such as floods, fires, and extreme weather events are very much like a war. They require the coordinated efforts of many people as well as the use of trucks, boats, airplanes, and other equipment. Many of the applications discussed above are used in these situations.

Summary

We have seen that the understanding of the size and shape of Earth is not new, but it has taken time to arrive at the level of knowledge that we have today. Geodetic concepts have been improved in recent years, and our ability to create accurate models of Earth has expanded the areas in which Geodesy is used.

We have also seen that Geodesy is at the heart of GNSS and GIS. Satellite positioning has grown rapidly and is continuing to evolve. Precise (survey grade) locations derived from GNSS is becoming a cornerstone of modern society. The surveyor of the future will need to be able to use the tool effectively and efficiently.

The next several lessons will reference systems, transformations between different systems, map projections, and the California Coordinate System. Later lessons in this period will cover GNSS fundamentals, error sources, planning and executing a static GNSS survey, planning and executing a Real Time Kinematic GNSS survey, and concepts around post processing the data.