PDH Academy

Introduction to GIS and GPS for Land Surveyors

4 Hours

PDH334

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Introduction to GIS and GPS for Land Surveyors Final Exam

1. The acronym GPS stands for:
    a. Global Positioning System
    b. Global Pole Stand
    c. Grand Project Survey
    d. Global Positioning Science
2. The “S” in the acronym GIS stands for:
    a. System
    b. Science
    c. Strategy
    d. System or Science
3. The United States GPS consists of all of the following segments EXCEPT:
    a. User segment
    b. Distance segment
    c. Control segment
    d. Space segment
4. Land surveyors use the GPS in applications or operations that include the following:
    a. Tracking the movement of ocean oil spills
    b. Synchronization of time for power transmission
    c. Search and rescue
    d. None of the above
5. A coordinate system is made up of all of the following EXCEPT:
    a. Scale
    b. Datum
    c. Ellipsoid
    d. Projection
6. In order to project spherical coordinates onto a planar coordinate system for mapping, at least one of the following properties must be sacrificed:
    a. Area
    b. Distance
    c. Direction
    d. All of the above
7. Method(s) used to collect GIS data include:
    a. Scanning paper maps
    b. Remote sensing
    c. COGO transformations
    d. All of the above

8. GPS technology involves the use of:
    a. Layer files
    b. NAVSTAR satellites
    c. Global Power Stations
    d. Local radio telemetry
9. GPS coordinates are captured and displayed in what coordinate reference system?
    a. NAD83
    b. NAD27
    c. WGS85
    d. WGS84
10. Coordinate locations can be collected by a land surveyor using what method(s)?
    a. Static surveying
    b. Real-time kinematic surveying
    c. Remote sensing
    d. All of the above
11. Satellite signals are radio waves that can be transmitted in which civilian frequency band?
    a. L1
    b. L2
    c. L3
    d. L1 or L2
12. GPS augmentation system(s) includes the following:
    a. WAAS
    b. CORS
    c. Both WAAS and CORS
    d. None of the above
13. Standard GPS accuracies without augmented correction systems are provided at which range with a 95% certainty of true position?
    a. 2 – 4 m
    b. 95 – 100 m
    c. 1 – 3 m
    d. <1 m
14. Vertical positioning errors using GPS are typically larger than horizontal positioning errors to what magnitude?
    a. 0.6 – 1.5 times
    b. 2 – 4 times
    c. 1.6 – 3 times
    d. None of the above
15. The three types of GPS roving receivers include all of the following EXCEPT:
    a. Recreational grade
    b. Mapping grade
    c. Commercial grade
    d. Survey grade

16. Collecting positions on features such as property boundaries, culvert inverts, roadway baselines, easements, or monuments is more likely to be conducted by:
    a. Municipal utility workers
    b. Surveyors
    c. Engineers
    d. Geocachers
17. Errors from GPS surveying can result from which of the following?
    a. Antenna strength
    b. Distance between your rover unit and the base receiver
    c. Signal bounce from an obstruction
    d. All of the above
18. The GIS primary functions performed on data include all of the following EXCEPT:
    a. Analyzing
    b. Distributing
    c. Querying
    d. Storing
19. Components of vector geographic information include:
    a. Attributes
    b. Projections
    c. Geometry
    d. Attributes and Geometry
20. When purchasing mapping or survey-grade GPS receivers, consideration should be given to all of the following factors EXCEPT:
    a. Type of data being collected
    b. Accuracy of the data needed
    c. Field software capabilities
    d. Ability to determine your position in relation to dinner after all data has been captured that day
21. GPS files generated from the use of survey receivers or remote sensors include which of the following?
    a. DXF
    b. LAS
    c. GeoTIFF
    d. All of the above
22. Image files and raster layers can be found in the following format(s):
    a. GeoTIFF
    b. GRID
    c. DEM
    d. All of the above
23. Geodatabases can hold all of the following EXCEPT:
    a. CAD datasets
    b. Rasters
    c. Coverages
    d. A spatial reference system

24. TINs, or Triangulated Irregular Network files, are a form of vector data used to simulate which one of the following?
    a. Point clouds
    b. CAD files
    c. Terrain surfaces from elevation points
    d. Irregular contour raster files
25. A metadata file accompanies a GIS file and provides identifying properties such as:
    a. Coordinate system information
    b. Raster resolution
    c. The extent or bounds of your data
    d. All of the above

PURPOSE

The purpose of this course is to provide a basic understanding of the term "GIS," and how this science is applied in land surveying. It is meant to familiarize surveyors with the terminology and industry lingo used by GIS Professionals, such that those composing or submitting responses to Requests for Qualifications or Proposals can better understand the scope of GIS or GPS services they need, or be asked to provide, and whether they have the in-house talent to perform such services. Essential concepts are initially discussed in order to understand the formats of geographical information and how it is used. Some of the more abstract scientific concepts and theories, while important, will not be covered. The course contains a short overview of the more popular GIS and GPS software and hardware. Surveyors should understand the differences between traditional electro-optical and GPS survey techniques. Lastly, it is meant to be an informative, practical and entertaining "quick study" for those deciding whether to integrate some of these skills into their career, or to possess a basic conversational language and understanding of the world of GIS and GPS.

COURSE OBJECTIVES

- Introduce surveyors to GIS and GPS concepts and terminology
- Explain the role of GPS in surveying
- Discuss current GIS and GPS products, along with their uses
- Familiarize readers with GIS & GPS file formats

Note: Sidebars and links to web sites are for your interest only. No test questions will arise from this material. The same cannot be said for the glossary provided at the end of the course!

DEFINITION AND A BRIEF HISTORY OF GIS & GPS

The acronym "GIS" can stand for Geographical Information Science or Systems. The science deals with the study of spatial and earth-referenced data, and how they relate in terms of proximity to surrounding data or objects. A system is designed to capture, query, analyze, manipulate, store and present all types of geographically referenced data. Any variable that can be located spatially, and increasingly temporally, can be referenced using a geographical information system. In the simplest of terms, GIS is the merging of cartography, statistical analysis, and database technology.

Credit for initiating the first operational geographical information system is given to the Canadians. The Canada Geographic Information System, or CGIS, was developed during the mid-1960's by their federal government to identify and inventory the nation's extensive land resources for existing and potential uses. This system was used to measure land areas and tabulate data, more than as a mapping tool. It became one of the first automated cartography efforts.

In 1967, the U. S. Census Bureau created the DIME program (Dual Independent Map Encoding) in preparation for the 1970 census. It created digital records of all U. S. streets to support automatic referencing of census records. It was during this time that cartographers and mapping agencies across North America, Europe, and Australia began to inquire about using computers that could be adapted to their needs in automating the creation and editing of maps. The redrafting of paper or other hardcopy medium maps by hand was a tedious and expensive process. In 1973, the world's first computer-made map was published in production series and according to established cartographic standards by the British Geological Survey and Ordnance Survey. However, due to the magnitude of the task, it was not until 1995 that Great Britain became the first to achieve complete digital map coverage (initially 230,000 maps) in a database.

Real growth in geographic information science and systems occurred in the 1980's when sufficiently powerful computer hardware was available, and prices had fallen enough to sustain a software industry. The first customers were forestry companies and natural resource agencies, driven by the need to inventory vast resources and regulate their use effectively. Just as new survey curriculums have evolved over the years from more traditional programs, geographic information science curriculums have evolved from more traditional degree programs such as geography, forestry, photogrammetry, and cartography. Users of GIS today are coming from increasingly different fields of study such as business, marketing, mathematics, healthcare, and surveying.

The Global Positioning System (GPS) is a system conceived in the 1970's by the United States Department of Defense, declared operational in 1995, and currently maintained by the United States Space Force. This system is freely accessible to anyone with a GPS receiver.
It has three segments:

1. *Space segment* – consists of a constellation of satellites orbiting the earth and transmitting signals denoting position and time.
2. *Control segment* – consists of worldwide monitoring and control stations that track and maintain the satellites in their proper orbits.
3. *User segment* – consists of the equipment that receives the satellite signals and determines the user's position, route, and time.

Another evolution in the communications world was occurring during the same period.

The United States Department of Defense also began a communications project in 1972 which later became known to the civilian world as "The Internet", or "World Wide Web" (WWW). By 1980, a European researcher had developed hypertext capability, allowing the use of the internet for anyone with access to a personal computer and the telecommunications network. Geographers were quick to see the value of the internet, and both GIS and the WWW have benefitted from each other. Geographic information systems benefit greatly in using the internet as a platform in which to disseminate information.

GIS internet mapping services allow users without GIS software or experience to address basic inquiries, and to create and print simple maps. Today, the trend is towards "Cloud Computing." Although many definitions exist, *Cloud Computing* is defined here as internet-based computing, whereby shared resources of data, software, media, etc. are accessed on demand through a network of off-site servers, as opposed to the more traditional methods of computing with software installed on individual computers. Service vendors provide storage of personal and business data, as well as access, on a pay-per-use basis.

An internet mapping service (IMS) as viewed from within Microsoft Edge

Throughout this course, we will discuss real-world surveying applications, discuss the importance of referencing data to a coordinate system so that it can be analyzed and modeled with meaning, explain the relevance of scale and resolution, discuss data collection methods using the Global Positioning System, introduce the functions of a geographical information system (GIS), and explain the components of vector geographic or spatial data. Multiple GIS software will be discussed, followed by the file and database formats available for manipulation and storage. GPS receivers collecting data for use in a GIS will also be introduced. A glossary is provided to summarize key terms as well as the many acronyms used in these fields.

APPLICATIONS FOR LAND SURVEYORS

The use of the United States Global Positioning System (GPS) as a global navigation satellite system for determining one's three-dimensional position and time has revolutionized the way we conduct business.

Land surveying was one of the first occupations to take advantage of this technology. When used by such skilled professionals, GPS surveying techniques and mapping data are of extremely high accuracy. GPS-based data collection is much faster than conventional surveying and mapping techniques, reducing the amount of equipment and labor required. Traditional surveyors appreciate this time and cost savings as well as the ease with which the data can be collected despite adverse weather or visibility conditions. Survey-grade equipment receives GPS satellite signals to survey baselines and structures for laying out highways or to survey large commercial or residential site development projects. GPS surveying is exceptionally viable for surveying coastlines where few traditional land-based reference points exist. GPS-based data collection is not limited to land surveyors. Offshore oil rigs depend upon global positioning technology for accurate hydrography surveys and incidentally, for mapping and containing oil spills such as that experienced with the Deepwater Horizon explosion in 2010.

Surveying a construction site using a GPS receiver unit
Source: United States Government

The use of airplanes mounted with GPS receivers and laser scanners for mapping square miles or hectares worth of terrain and objects on the ground is considered a form of remote sensing. Now with the use of unmanned aerial vehicles (UAVs) covering smaller areas with similar scanners, the line between remote sensing and surveying is becoming blurred. UAVs, well-known as *drones*, can now scan and subsequently map areas to near survey-grade accuracy. They are used at construction sites for computing earthwork volumes and assessing the progress of work. Software is used to extract and process the data captured to produce maps and to create a three-dimensional replica of the site for further analysis or decision making.

Pre-flight check of a UAV
Source: USGS

To appreciate the many applications of surveying using the GPS, we will first need to grasp certain concepts, become knowledgeable on specifications, and learn a little about the products in use today.

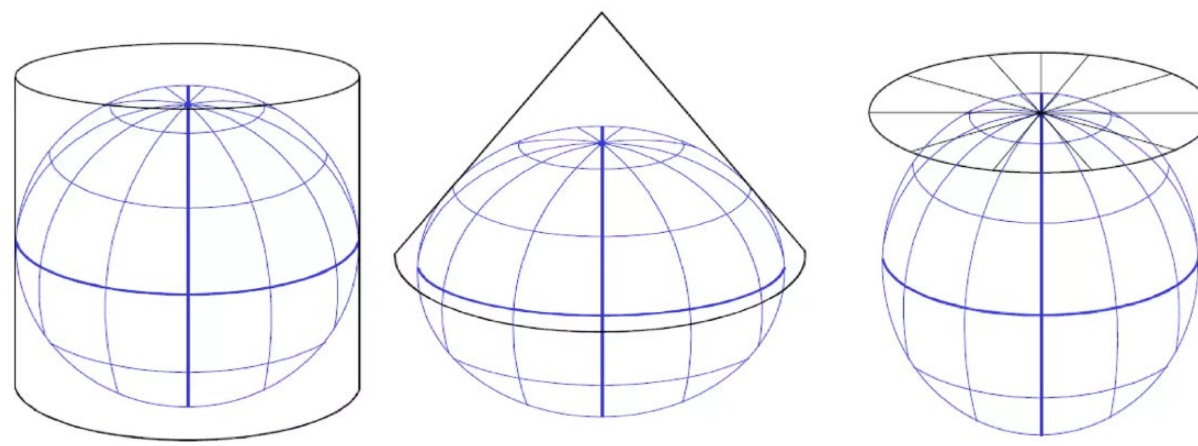
GEOREFERENCING, COORDINATE SYSTEMS AND MAP PROJECTIONS

Surveyors and users of a GIS alike are interested in analyzing spatial relationships among real-world objects. Unlike a computer-aided design (CAD) drawing which can reference every item drawn from coordinates of 0,0 on an arbitrary planar coordinate system with no projection, features in a GIS need to be referenced to the correct location on the earth's surface according to established coordinate systems. Referencing data to the earth with coordinate systems allows for proximity analyses (e. g. buffering), address and feature searching, overlay analyses (combining two spatially aligned layers to create a new layer containing attributes of both), and network

analyses (how linear features are connected and how efficiently resources use the linear network) to be conducted. Data layers in the same project must be referenced to a common coordinate system so that they are geographically aligned with other layers in order to conduct most spatial analyses. The process of assigning a coordinate system is called *georeferencing*. A projection, ellipsoid, datum and units make up a map coordinate system. This section will present only a broad discussion of map projections, as entire courses are taught on this subject matter.
The objective is to introduce concepts related to popular coordinate reference systems.

The most common coordinate system is the spherical coordinate system measured in latitude and longitude, otherwise known as a **Geographic Coordinate System**. Its origin is where the Greenwich prime meridian intersects the equator. Because it can be impractical to perform measurements in spherical coordinates, geographic data is projected onto a planar coordinate system, often called Cartesian coordinate systems, in order to make maps. Mathematical formulas are used to accomplish this. To visualize this concept, imagine shining a light on a globe with a paper grid, or graticule, wrapped around it while its shadow is projected on a wall. If the globe were transparent except for land and the grid lines, a 2D map of the continents and grid would appear, hence the term map *project*ion. There are different types of projections based, in part, upon geometry. These include planar, cylinders, and cones (conic). Each type is based upon at least one point of contact with the globe, whether it be a point or a line. Cylindrical projections, for instance, can have the equator or a central meridian as their tangential line of contact.

Cylindrical Example: Mercator	Conical Example: Perspective	Planar/Azimuthal Example: Orthographic



Types of Projections

Of course, simplifying a geographic coordinate system to a Cartesian coordinate system comes at a price. All projections (including the one on the wall) result in distortion by at least one of four spatial properties:

- area,
- shape
- distance
- direction

If you choose a projection that preserves true distances for instance, you will sacrifice accuracy in at least one other property. Other projections seek to minimize overall distortion but must sacrifice all of the four spatial properties in doing so. Hence, there are multiple projections generally classified according to the geometry and spatial property they preserve. Common types of map projections include equal area projections like **Albers Equal Area Conic**, which preserves area, and conformal projections like cylindrical **Mercator**s and the **Lambert Conformal Conic**, which preserve shape. Another very popular projection is a **Universal Transverse Mercator (UTM)**. This is a type of Mercator projection system developed and used by the U. S. Army and the U. S. Geological Survey (USGS) to make topographic quadrangle maps at a 1:100,000 scale. Equidistant projections preserve distances such as meridians or parallels. Azimuthal projections preserve direction from one point to all other points. Another common reference system is the **State Plane Coordinate System** with over 120 zones dividing the entire United States, Puerto Rico, and the U. S. Virgin Islands. This system uses either a Mercator or the Lambert Conformal Conic Projection to transform the spherical shape of the globe onto a flat surface. Projection information is usually stored in a separate file along with the data itself.

If you are a surveyor, you've likely studied about ellipsoids. An ellipsoid is a geometric simplification of the earth's surface. It is a sphere with one axis longer (typically, the equator) than the other. It is used along with a datum to provide a frame of reference for measuring locations upon the earth.

Most surveyors are familiar with datums. Horizontal datums have been traditionally defined by an ellipsoid and the ellipsoid's position relative to the earth. Horizontal datums are either earth-centered or local. Local datums are chosen when the area surveyed is relatively close to its origin, thus providing better local accuracy. Earth-centered datums have the origin placed at the earth's known center of mass and are more accurate over all the earth.

Common reference systems include:

- **North American Datum of 1927 (NAD27)** (local) with the **Clarke 1866** ellipsoid
  This datum has its origin centered at Meades Ranch, Kansas.

- **North American Datum of 1983 (NAD83)** (earth-centered)
  with the **Geodetic Reference System of 1980 (GRS80)** ellipsoid
  The latest State Plane Coordinate Systems reference this datum.

- **World Geodetic System of 1984 (WGS84)** (earth-centered) with the **WGS84** ellipsoid
  This system originally used the GRS80 ellipsoid but has undergone refinements since its initial publication. These refinements resulted in a slightly more precise position of the earth's center of mass. The WGS84 currently uses the WGS84 ellipsoid and the associated International Terrestrial Reference System, which constantly monitors the positions of global reference stations to account for the earth's crustal movement, or continental drift. It is currently the coordinate reference system used by the U. S. Global Positioning System, which will be discussed further in the text.

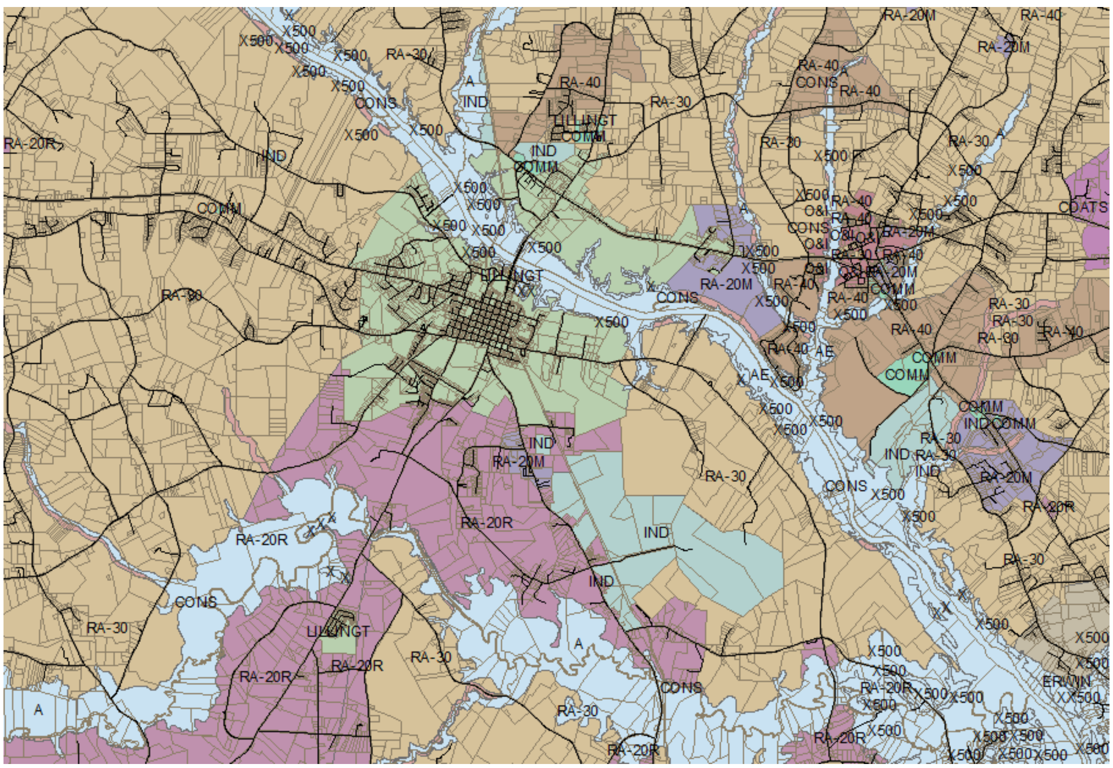
Of course, all work in a Geographical Information System must have units of measurement, much like a CAD drawing must have working units. These units define the working area, or design plane (for CAD)/domain extent (for GIS) for which calculations are performed.
The resolution in CAD drawings is specified by a user-defined positional unit, such as feet, meters or thousandth of each. The smaller the positional unit, the smaller the design plane in which to work. In a GIS, the extent can be manually set using known boundary coordinates according to the coordinate system in which you are working (e. g., Northing/Easting or Latitude/Longitude). In some Systems, the default option automatically sets to the extent of your geographically most expansive input layer.

Conveniently, some (if not most) GIS software includes many different projections and coordinate systems with which to georeference or convert coordinate locations. Fortunately, an in-depth knowledge of map projections and coordinate systems is not necessary to work in a geographic information system. Much like survey standards for CAD drawings can be predetermined by your client or governmental agency, coordinate systems for GIS calculations and maps typically follow predetermined standards.

WORKING WITH SCALES AND RESOLUTIONS

Choosing the proper scale to produce maps in a GIS is just as important as plotting computer-aided design (CAD) drawings at the proper scale. Cartographers and GIS users need to produce readable and/or printable maps which clearly illustrate their purpose. A city may be illustrated as an area feature (polygon) on a large-scale map, whereas it may only need to be represented as a dot, or some other symbol representing a point feature, on a small-scale map. Zoom tools are provided for interactively setting the display, just as they are in a CAD system.

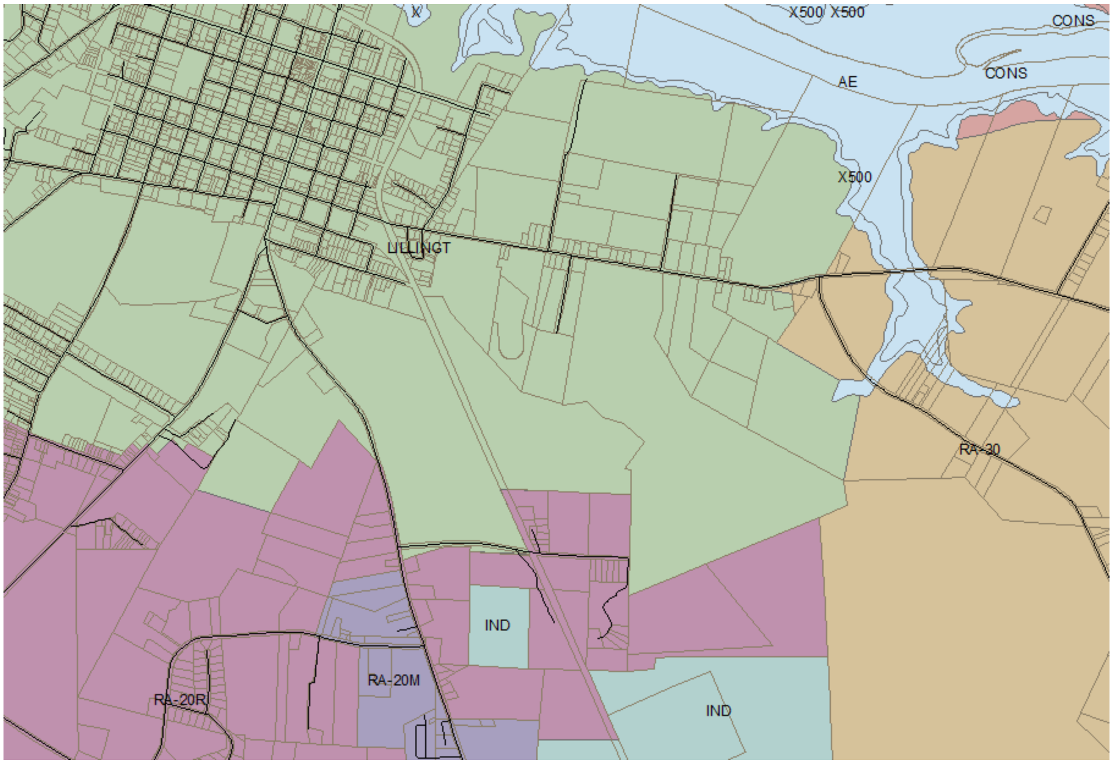
Unique to some geographical information systems is the ability to set a minimum scale at which certain layers are displayed. This prevents clutter on your map by restricting the display of features until a more appropriate scale is reached. As you zoom from a small to a large-scale map, more features automatically appear instead of having to turn individual layers off in a table of contents or layer tree. The images below demonstrate the importance of cartographic skills in map presentations. The map below has too much information. Parcel information is of little use at this scale, and labels are too clustered to read.



1:100,000 scale map showing roads, parcels, multi-colored planning zones with labels, and flood zones with labels

At a scale of 1:100,000, the map above would be easier to read once the parcel data and labels have been removed. A title would be appropriate to define the area of interest, accompanied by a legend to distinguish zones. The viewer can get a general sense of the type and limits of development within the area.

At a scale of 1:24,000, parcel information and labels are appropriate, and provide specifics on the type and extent of zones for the map below. The scale and labeling are such that they allow the viewer to distinguish individual parcels and zones.



1:24,000 scale map showing roads, parcels, (colored) planning zones with labels, and flood zones with labels

In working with images, choosing the proper scale at which to view or print maps is especially important. This is because a desirable viewing or printing scale is dependent upon spatial resolution. Resolution represents the area on the ground that can be seen from a sensor (camera lens, satellite, etc.) above. The spatial resolution of data collected is always increasing with better data capture technology, increased storage capacity of hard drives, portable memory devices, access to cloud servers, and decreasing costs. Yet, where large data collection efforts are undertaken (usually by national agencies) and the results made available to many users across the United States, they may be of lower resolution than that of data collected through efforts initiated by local governments or private entities for smaller regions. Several states have made appropriations over the years to collect their own elevation, land use, or hydrography data. Image resolution can be different at the same scale and vice-versa, though a relationship exists. At smaller scales, images can be of low-resolution quality because a high level of detail is not required. Such is the case when working on a national or regional scale. Think of it as taking a "big-picture" approach to analyses. Zooming in on the display to increase the viewing scale will enlarge objects but will not increase the level of detail and can lead to a blurred or pixilated view of low-resolution images or maps. Whereas at larger scales, high-resolution images are needed in order to view detailed information or provide accurate calculations. Now you are studying the trees within the forest, so to speak. Below is an illustration of a photograph at two different scales, but with the same cell size, or spatial resolution.

Scale: 1:10,000
Cell size: 61 cm

Scale: 1:2,000
Cell size: 61 cm

For reference, large scale maps have ratios of 1:25,000 or greater. Medium scale maps have ratios between 1:50,000 and 1:100,000. Small scale maps have ratios smaller than 1:250,000. Depending upon the source and time of creation, elevation surfaces, aerial photographs and other images have resolutions of 30 m, 10 m, and to an increasing extent, 1 meter. These abbreviated descriptions refer to images with a cell size, or ground resolution, of 30 m x 30 m, 10 m x 10 m, and so on. (Because imagery is available internationally, it is typically measured and referred to in the International System of Units (SI), or metric units.) By today's standards, low-resolution images are considered those of 30 meters and coarser. High-resolution satellite images are those of 1 meter and finer. Of course, the resolution of your computer screen (the number of pixels per inch) affects the scale at which your images are used for presentation, and the resolution of your printer/plotter (dots per inch or dpi) is what finally dictates the scale you will want to use for the printed map to be readable.

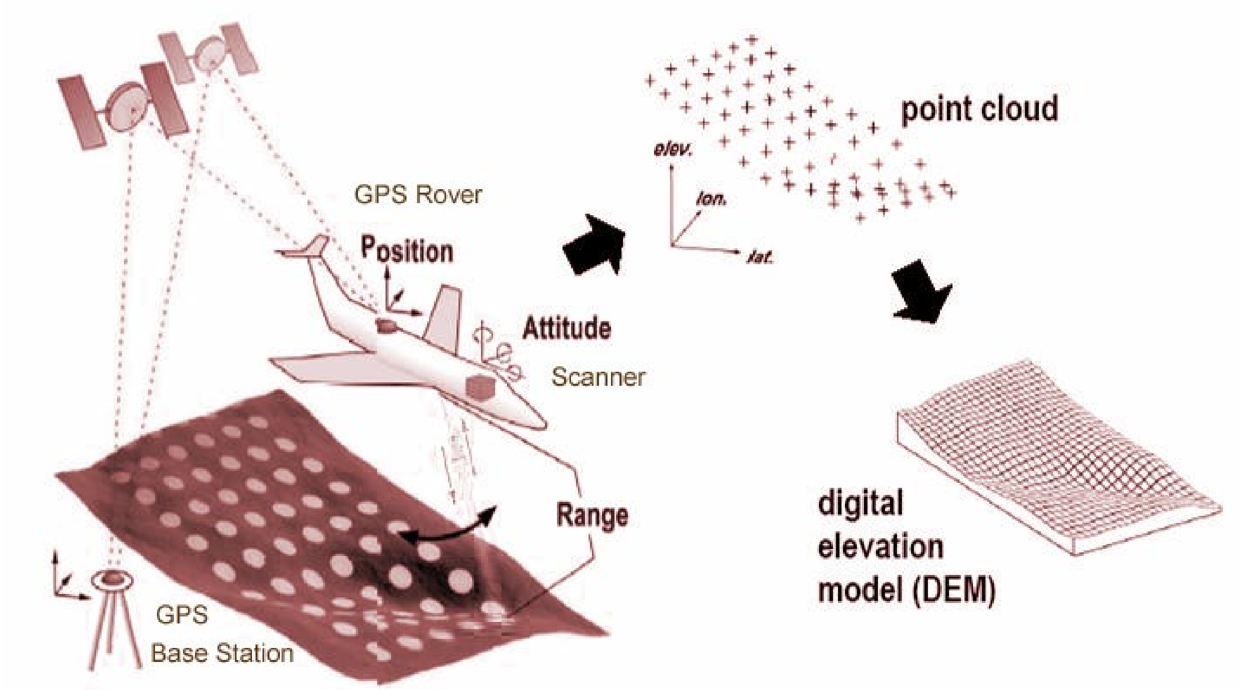
DATA COLLECTION USING THE U. S. GLOBAL POSITIONING SYSTEM

So how is data collected for use in a geographic information system? Digital data can be created by scanning paper maps or aerial photos, imported from spreadsheets or other databases, remotely sensed from satellites, and/or captured in the field from traditional electro-optical survey instruments, or more directly, from global positioning system receivers. We will briefly discuss the less obvious methods of data collection.

Geographical information systems utilize traditional ground survey data in vector format.

Total stations use optics to capture geographic data by measuring distances and angles in coordinate geometry, or COGO for short. The COGO system uses survey-style bearings to measure angles and distances, both to define the geometry of areas and objects. It a system widely used in North America to represent property parcels. COGO measurements are geometrically transformed into *x*, *y* and *z* coordinates for use in a GIS. More often, they are manually entered from hardcopy maps and documents of survey plats or legal descriptions before transformation.

A large portion of GIS data is captured via remote sensing. Remote sensing is the measurement of physical, chemical and biological properties of objects without direct contact. It is a practice that involves sensors mounted on satellites, aircraft, balloons, and other devices to detect (primarily) visible, infrared, and thermal radiation reflected or emitted from sources on or below earth. Different bands of radiation define different properties. Images resulting from remote sensing are used to decipher properties such as land cover, mineral composition of rocks, forest types, crop health, and surface water temperatures. **LiDAR**, or **Light Detection and Ranging**, is a type of remote sensing using light waves transmitted from aircraft-mounted sensors to detect the height of objects on the ground, or the ground itself. GPS receivers reside on or within the moving device as well as on the ground to receive signals from the satellites that pinpoint the locations where these heights are detected. Increasingly, this type of remote sensing is being conducted through the use of unmanned aerial vehicles or *UAVs*. Digital elevation models can be created from LiDAR data. LiDAR elevation data taken by airplanes are considered accurate to 0.61 meters (2 feet). LiDAR elevation data taken by UAVs, otherwise known as *drones*, can be accurate to near survey-grade resolution and costs much less than a small plane to fly. The data is used extensively by civil engineers for designs requiring more accurate elevations than what USGS topographic maps could provide, or for supplementing ground surveys in areas where it would otherwise be impractical to collect field data.



LiDAR data collection workflow. GPS receivers are located on the ground and in the plane to collect and correct position coordinates. A laser scans the ground to collect elevation data.

Digital Elevation Model of sound and coast off North Carolina (20 ft grid cell)

Source: NC OneMap (2019). North Carolina Department of Information Technology, Government Data Analytics Center, Center for Geographic Information and Analysis.

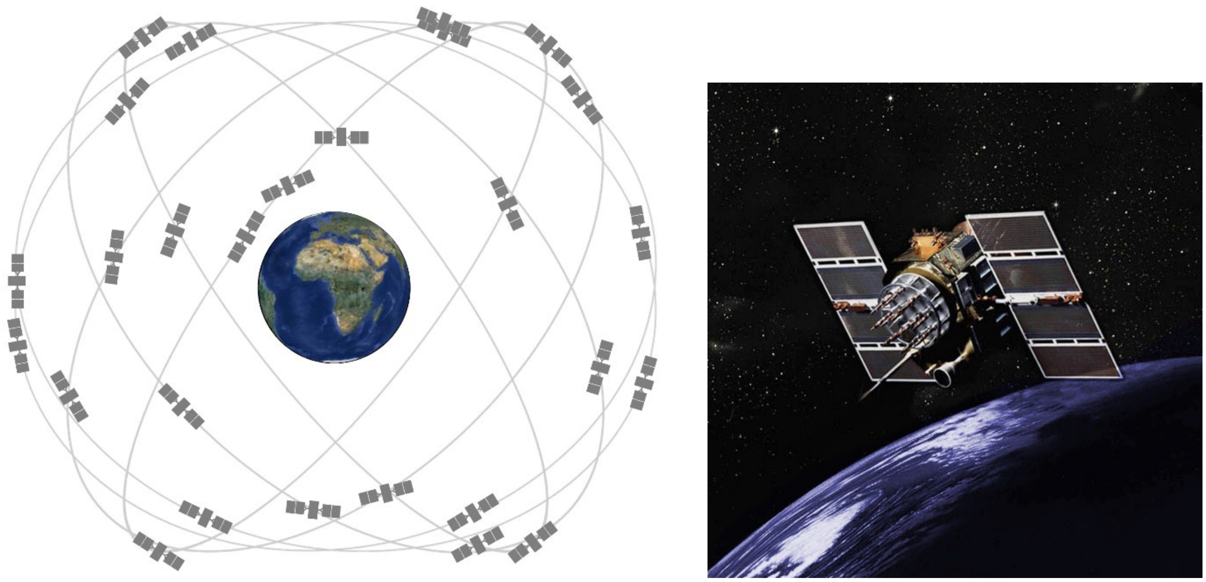
Survey data is increasingly being collected using the United States Global Positioning System. As mentioned, this system can provide three-dimensional positioning data for the same features as those conducted with traditional survey techniques. Surveying with this system can, as with remote-controlled total stations, be performed using a single surveyor. This next section explores the history and technology behind the science used to capture GIS survey and mapping data, the types of surveys conducted using the U.S. global navigational satellite system (GNSS), the augmentation systems used to assist the surveyor or mapper, then some of the more popular product vendors.

GPS TECHNOLOGY & METHODS

GPS equipment is much more available and affordable to the general public than ever before. People have GPS "units" in their cars or on their boats to provide directions, on their bicycles and wrist watches to plan routes and follow them, and in cell phones as an emergency locator feature. To the average user, these are just high-tech gadgets. Yet, what is really interesting is the science behind how these gadgets operate. The Global Positioning System is a space-based global navigation satellite system that provides location and timing information in all weather, anywhere on the Earth where there is an unobstructed line of sight to three or more (usually four) satellites. The backbone of the GPS is a constellation of 24 satellites, identified as the *Navigational Satellite Timing and Ranging* (NAVSTAR) system, located in precise orbits, each approximately 12,550 miles above the earth and orbiting it once every 12 hours. These satellites transmit high-frequency radio pulses at very precisely timed intervals. This allows a GPS receiver to determine its location when locking in on the signals. How? By measuring the time it takes for a radio wave to reach a GPS receiver, one can determine distance to the satellite, and thus relative location on earth. Radio waves travel at the speed of light. The time is multiplied by this speed (roughly 186,000 miles per second) to obtain distance. However, to pinpoint a three-dimensional location, at least three satellites are used in a process called *triangulation*. To relate, triangulation is also used to locate a cell phone user from antennae towers though historically, not as accurately when using non-GPS integrated phones. (This is changing with the advent of 5G cellular radio technology.) In addition to the satellites, five worldwide ground stations monitor the satellites to ensure they maintain their proper orbits and clock time.

Triangulation or Trilateration?

To the purist, the 3-dimensional location of a position using satellites is actually termed "trilateration". This is because the position is determined using distances instead of angles. Trilateration uses the intersection of three sphere surfaces with known centers and radii of the satellites in narrowing the location of a point on the earth. The term "triangulation" is used to better relate the concept.



GPS constellation of satellites (left) & one of the first satellites in orbit (right)
Source: United States Government

Radio waves are transmitted by the satellites to GPS receivers using civilian frequency bands measured in units of megahertz. These signals are referred to as L1 and L2. The L1 signal has been available for years and will be available for the foreseeable future. It is transmitted at a frequency of 1575.42 Mhz. The L2 signal is one that sometimes requires a code to gain access to its military-grade accuracy. It is transmitted at a frequency of 1227.60 Mhz. A lower frequency translates to a higher wavelength resulting in a signal that can pass through obstacles such as cloud cover and trees more effectively. These frequency bands were chosen to minimize the effect of weather on GPS signal propagation. To achieve the highest level of accuracy, survey-grade receivers are often equipped with dual receivers. The federal government continues to modernize the Global Positioning System by launching replacement satellites that can transmit new and more powerful civil signals. The L2C is one such signal that is provided specifically for civilian, commercial use.

These signals transmitted as radio waves can talk with the receiver but need to be decoded before talking with the user. The receiver decodes the satellite output into a device-readable binary format. Software is installed on your computer or device to which the receiver is attached that will decode the binary comma delimited lines of text, or *sentences*, as is known in GPS parlance. Many different formats exist that capture data on location, elevation, time, date, speed, course and sometimes data on the satellites themselves. Latitude and longitude coordinates are not always displayed in sentences we recognize as degrees, minutes, seconds or decimal degrees.

Global positioning surveying is used for topographic surveys, engineering surveys, and construction surveys. The first techniques for land surveying using the Global Positioning System in the 1980's followed the traditional static data collection methods whereby an individual held a receiver with an antenna and waited to gain enough satellites within view to obtain an accurate reading. This process was repeated after walking to the next point of interest. While this method provided for unparalleled locational accuracy and reduced labor, it also took many hours to collect data and even longer post-processing times.

Conceived in the late 1990's, real-time kinematic or *RTK surveying* enabled surveyors to set up a temporary, stationary base receiver that not only receives satellite signals but also transmits correction signals to a roving receiver held by the surveyor. Thus, a minimum of two receivers are required. The temporary base receiver is set up on a known monument or point whose coordinates are fixed and determined by other precision methods in surveying. The rover receiver also receives satellite signals, but as its name implies, is free to move around. Since the stationary receiver knows its location, it can use information it receives to correct timing errors coming from the satellite signals to the roving receiver. Multiple roving receivers can work from the one base receiver. Communication between the base receiver and the roving receiver(s) allowed the surveyor(s) to cover much more territory in a shorter period of time and to a high degree of accuracy. Specifications exist from government agencies or committees limiting the distance the rover can be from the base station while collecting its position. Often, antennae were attached to the back of moving devices such as all-terrain vehicles while traversing over acres or hectares of land. Readings can be taken every few seconds. Today, we also have RTK surveys being conducted using drones. As the technology evolved, real-time networks and permanent base stations became more available and eliminated the need for temporary base stations to be manned. Real-time kinematic surveying is referred to as a type of *differential GPS* used to augment and increase the reliability of your positional accuracy.

As you can imagine, distortion occurs in the signals when traveling that kind of distance through the atmosphere (especially the ionosphere). Furthermore, clocks are occasionally off by a fraction of a second. While this does not seem to be of concern, consider that the distance measured by this offset can lead to errors of a few hundred meters! Fortunately, there are augmentation systems available to improve signal availability and accuracy.

If you've heard about a "WAAS-enabled" GPS unit, it refers to the **Wide Area Augmentation System**. This is a satellite-based augmentation system operated and maintained by the Federal Aviation Administration to support aircraft navigation across North America. In brief, signals from GPS satellites are received at widely spaced ground reference stations across the country. They are then forwarded to master stations through a ground communications network. At the master station, augmentation messages are generated which contain information that allows GPS receivers to remove errors in the GPS signal. Transmission back to the receiver is through its geostationary satellites, or satellites in a fixed position over the equator. Thus, the WAAS requires a clear view of its satellites in the southern horizon. This system is optimal for use on open land (i. e., fields) and on the oceans. It is one of the more common U. S.-based augmentation systems used in GPS receivers to enhance accuracy and reliability of position estimates.

Ground-based augmentation systems also exist and are known as *Differential GPS*. They provide a network of land-based receiving stations by which to conduct real-time kinematic surveys. There is no need for the signal to return to the satellite.

One such ground-based system is operated and maintained by the National Oceanic and Atmospheric Administration. The U. S. **CORS** network stands for **Continuously Operating Reference Stations**, and archives and distributes GPS data for precise positioning from almost 2,000 independently owned and operated tracking stations worldwide. Over 200 private, public and academic organizations contribute the data. The Administration analyzes and distributes the data free of charge. Engineering and survey firms as well as government agencies use this system to improve the accuracy of their surveys. Instead of providing a temporary base receiver, RTK surveyors rely upon this network of reference stations served by a central computer system. The roving receiver(s) contacts the reference station's central computer system (sometimes referred to as a *virtual reference station*) through a cellular link and starts receiving a unique correction based upon its location in the network.

There are other global navigational satellite systems as well as GPS augmentation systems available worldwide, both government and commercial, for which coverage is beyond the scope of this paper.

GPS ACCURACIES

So, just what kind of accuracy do the global positioning augmentation systems provide these days? Well, that depends, in part, upon the augmentation system used. The WAAS is currently providing a horizontal accuracy of between 0.6 – 1.5 meters at least ninety-five percent of the time via its 25 ground reference stations and 2 master stations. (GPS accuracies are typically expressed in SI units.)

Whether your coordinates are processed for correction in real-time (field processing), as discussed above, or post-processed back at the office affects accuracy. The web-based **Online Positioning User Service (OPUS)** offers free post-processing (correction) of GPS datasets to centimeter-level accuracy using CORS information.

Aside from augmentations systems, the federal government's GPS accuracy is always improving. Those who have used GPS receivers for some time, whether for surveying or for recreation, can appreciate the improvements in GPS accuracy to date. Standard GPS, without augmentation, went from an original accuracy of +/- 100 meters in the 1990's to currently between 2 – 4 meters of true position with 95% certainty.

Selective Availability (SA)

In the 1990's, the US military introduced errors into the GPS in order to degrade civilian accuracy on a global basis. The intent was to prevent the hostile use of GPS from enemies wanting to use it to make accurate weapons. "Noise" was introduced into the satellites' atomic clocks, offsetting signal timing and thus, position accuracy. In May 2000, President Clinton announced a decision to discontinue the use of SA, increasing positional accuracy from +/-100 meters to the current accuracies.

GPS accuracy is usually talked about in terms of horizontal accuracy. Vertical accuracies in regard to heights can also be measured with satellites but are typically lower. If we go back to the discussion on ellipsoids, remember that an ellipsoid is a 3-dimensional geometric approximation of the earth's surface. Global Positioning System vertical observations are measurements of ellipsoid heights using the WGS84 ellipsoid, as an indirect approximation of sea level. Thus, any measurements made from an assigned ellipsoid will be offset by the difference between the ellipsoid and the natural, irregular shape of the earth (or your GPS antenna height). To measure vertical heights (and to provide significantly more accurate horizontal positions), a fourth satellite is necessary. As such, remote sensing or traditional surveys are typically used to provide more accurate heights, or elevations. The WAAS can produce a vertical accuracy of between 1 – 2 meters with a 95% certainty. The OPUS achieves a post-processing of coordinate datasets in centimeters, both horizontally and vertically. In general, errors in elevations provided by GPS units are expected to be between 1.6 and 3 times larger than errors in horizontal positioning.

The augmentation system accuracy and the type of processing available to the user depends upon what a GPS receiver unit supports. There are three kinds of GPS roving receivers:
1) recreational grade, 2) mapping grade, and 3) survey grade. Recreational grade GPS receiver units are the least expensive and have always been portable. They are used primarily for navigation and can be purchased at sporting goods stores. They are good for collecting coordinates quickly, at accuracies of within a few meters using real-time WAAS correction. Post-processing using differential correction cannot be performed with most of these units. Casual users of recreational grade units include hikers, geocachers and boaters. Mapping grade receivers are for more serious users and are used for collecting feature coordinates for what will become points, lines or polygons in making GIS maps. They can be set up with filters to ensure a stronger satellite signal before capturing coordinates. The trade-off is that points may take longer to collect (i. e., to get a "fix" on a satellite). Traditional mapping grade receivers, such as

those produced by Trimble, are capable of accuracies less than a meter after correction. Tablet PCs and "smart" phones with GPS chipsets in them fall into this category. When connected to certain GPS antennae, these devices can compete in accuracy with traditional receivers. Municipal workers and underground utility surveyors for instance, lean towards using their own tablets and smart phones with the operating systems and "apps" (i.e., applications) of which they are accustomed. Some companies have adopted a Bring Your Own Device (BYOD) strategy, which uses company-provided software to run on their employees' personal devices. Not to be outdone, the traditional receivers are typically more durable, waterproof, have better visibility in sunlight, and hold longer-life, hot-swappable batteries. Both can collect attributes and take photos. Survey grade receivers are used primarily by licensed professional surveyors to provide high-quality property boundary delineations and locations, such as culvert inverts. Unlike traditional surveying, constraints of weather or reduced sunlight between stations is not affected with GPS surveying.

While we are on the subject of accuracy, it should be noted that errors resulting from traditional surveying techniques are relative to each other and cumulative. Errors are distributed between each point that defines the boundary to correct the survey so that an area can be considered closed. By contrast, errors in GPS surveying are independent with each position captured. While total stations can provide measurements accurate to 1 millimeter, GPS receivers using real-time kinematic (RTK) survey techniques for instance, can provide horizontal accuracies to within a few millimeters, and vertical accuracies to the centimeter level after correction.

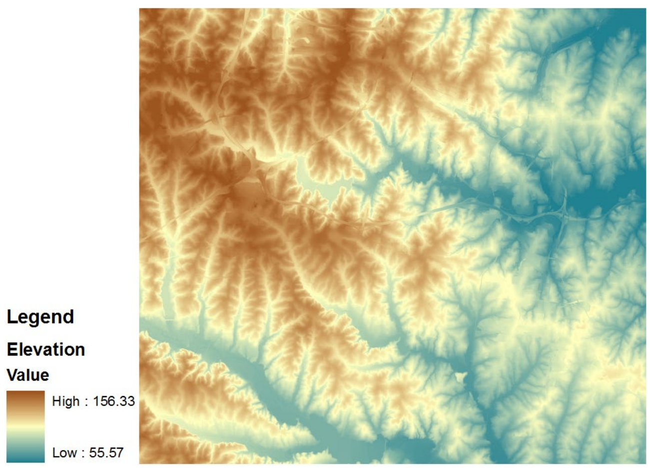
Other factors are outside the government's control, such as antenna strength of the GPS receiver, solar flares, the distance between base (reference) stations and the receiver, and the number of base stations available. You can check the NOAA Space Weather Prediction Center website for updates on predicted solar or other radiation events. Additionally, once a signal gets to earth, it may bounce off buildings or dense tree canopies before reaching a receiver. This is called *multipath error*. As such, these are local errors that degrade GPS accuracy and cannot be corrected. Fortunately, they are miniscule in relation to other errors. Bear in mind, that you may not receive a signal at all, if you are trying to collect, or "log", coordinate locations inside a building or tunnel. With that said, the U. S. government continues to develop stronger satellite signals, while manufacturers of GPS products are ever improving their devices to be more sensitive to these signals.

FUNCTIONS OF A GIS

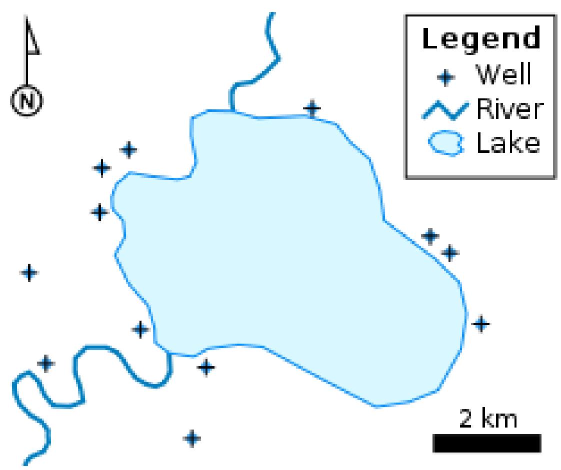
A Geographical Information System is powerful in that it provides many functions for finding real-world solutions to problems using provided data. Below are six functions of most systems:

1) Capturing Data - The ability to capture geographic (coordinate) and tabular (attribute) data using various means is what makes the System versatile. Surveying is just one means.

2) Storing Data - There are two basic formats for representing and storing data: vector and raster. Vector files represent cartographic features much the same as maps or scaled drawings do – with points, lines, and areas. Each type of geometry represents a separate feature class. Vector files provide discrete representations of reality with known coordinates tied to their features. Raster files represent a grid of rows and columns, with each grid cell possessing some value. These grids may provide discrete or continuous representations of reality and may or may not be referenced to known coordinates at the time of creation. Many raster formats exist. Imagery in a GIS is only available in raster format. Cell values contain color band data. As digital photographs contain more detail with an increased pixel count per 4 inch x 6 inch image, raster images can also contain more detail with an increased cell count per unit area. Rasters deal with resolution in terms of cell size or ground resolution. So, a 1-meter raster means that each pixel represents 1 m x 1 m on the ground. The level of detail is more accurately termed the *spatial resolution* of the raster and depends upon the device used to capture the image.

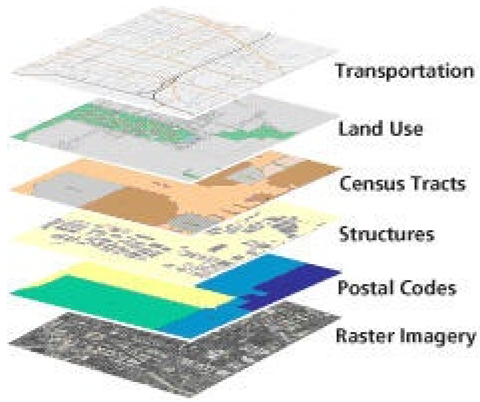


Raster layer of terrain relief



Vector layer representing all feature classes

Both vector and raster formatted files are presented as layers in a GIS. These layers contain both the geographic and attribute data. Attribute data is stored in tabular form within a database. Data layers are stored in several different formats, which will be discussed later within the text. Layers can be overlaid and spatially aligned for performing queries, analyzing to produce new data, and simply showing relationships that may otherwise be overlooked with separate paper maps, tables, or other more traditional sources of information.



GIS Layers
Source: Fire Program Analysis

3) Querying Data – A GIS must have commands or utilities for finding features with specific attributes. Common commands include selecting features by attributes or by location. Selections can also be based upon conditions. For instance, selections can be based upon a previous selection, or upon the intersection or union of two or more features, either within the same layer or from different layers. Raster cells can be selected by common or unique attributes. They too, can be selected based upon conditional statements specified by the user. Some Systems have the ability to draw graphics, upon which they also, can be used to select certain features or cells within a layer. Another way to query in a GIS is by measuring features.

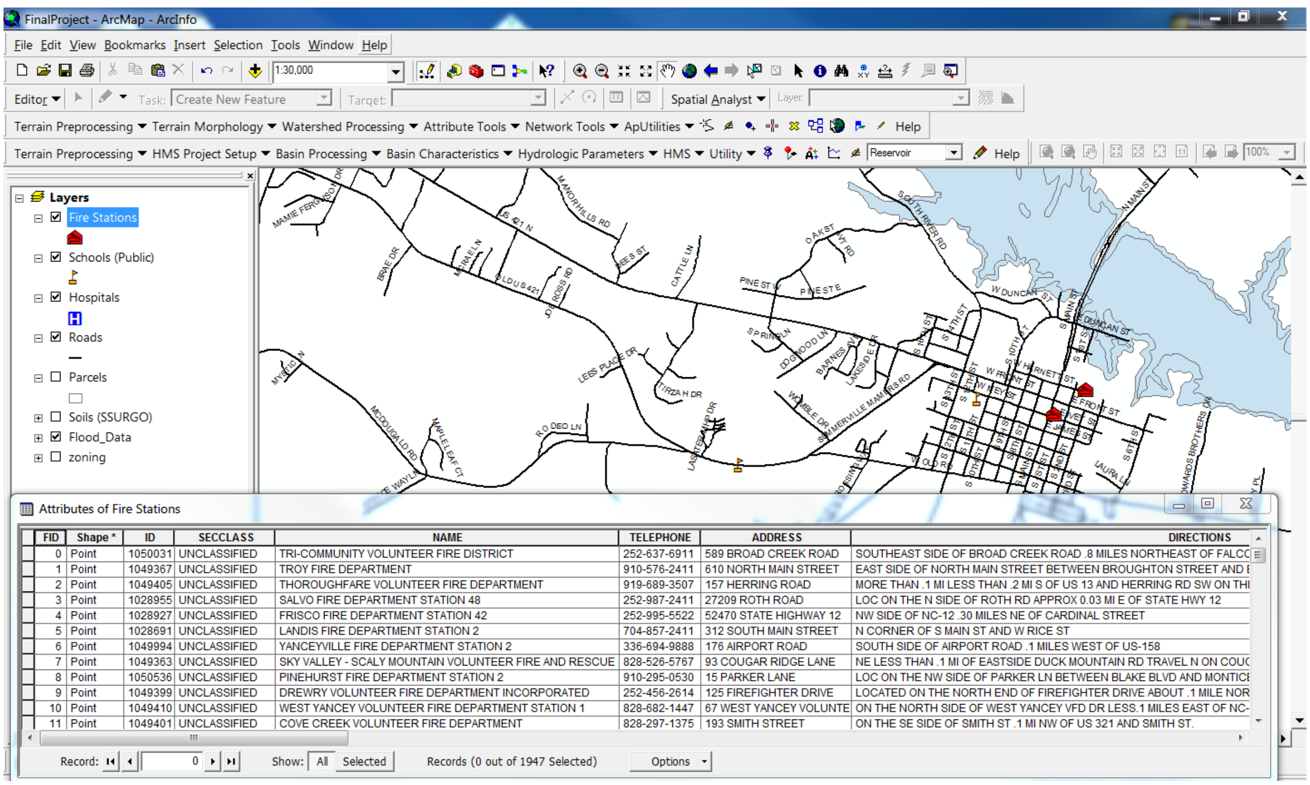
4) Analyzing Data – A GIS must be able to identify spatial relationships between multiple datasets. Geoprocessing is defined as an operation performed on geographic, or spatial data. It involves an input dataset and a tool or command to analyze and generate new information resulting, in an output dataset. Examples of geoprocessing would include placing a 50-foot buffer around streams to avoid development in these areas, or interpolating a raster elevation surface from measured elevation points. Spatial queries, as explained above, are also considered to be a geoprocessing operation.

5) Displaying Data – A GIS must have an interface and graphics capable of displaying results at different scales and with multiple symbology. It can often simulate 3-D images from 2-D images using shading techniques. A GIS is capable of 3-D modeling when a third, and often fourth dimension, is provided.

6) Outputting Data – Most Systems provide options for results to be displayed in multiple formats, such as maps, tables, reports and graphs.

COMPONENTS OF VECTOR-BASED GEOGRAPHIC INFORMATION

Survey data can be collected for creating digital elevation or surface models in vector format. There are three basic components to vector formatted geographic information. They are geometry, attributes, and behavior. Geometry represents the features associated with real-world locations. These features are broken down into point, line, or polygon classes, each sharing a common coordinate system. Attributes are the general names given to values, or properties, associated with each unique feature. An example of attributes for a water feature, such as a lake, would be its size or name. Behavior deals with the rules on how adjacent or connecting features in a vector file are to behave. These spatial relationships are often referred to as *topology*. For instance, property boundaries often exist as area features. A typical behavior is that these areas cannot overlap one another. Line features such as interstates may have a rule prohibiting them from intersecting city streets.



An attribute table (database) for a vector layer of fire station locations within a GIS.
The table of contents lists each layer (dataset) to the left.

GIS PRODUCTS

During the 1980's as GIS was becoming more mainstream, software companies such as Intergraph with Bentley Systems, Inc., ESRI, Inc., and ERDAS, Inc. emerged as commercial vendors of GIS software, incorporating many of the original Canada Geographic Information System features. Autodesk, Inc. would follow in the next decade. Below are some of the early and on-going vendors of commercial software in use today.

ESRI, Inc.

ESRI, or The Environmental Systems Research Institute, Inc., is a privately held company founded in 1969 and headquartered in Redlands, California. ArcGIS for Desktop 10.8.2, with its famed ArcMap, is the last of the supported desktop versions of this family of products and is scheduled to be retired March 1, 2026. Users are expected to migrate to **ArcGIS Pro**, the company's full-featured professional application to provide analysis, mapping, file management, content sharing, data and coordinate system conversions, and geoprocessing. This architecture is licensed at three levels: Basic (formerly called ArcView), Standard (formerly called ArcEditor), and Advanced (formerly called ArcInfo). ESRI also offers a version called **ArcGIS Online**. This cloud-based server provides online mapping and analysis with an ever-growing number of capabilities. You can access ArcGIS Online through web browsers and mobile devices. It works seamlessly with ArcGIS Pro to share 2D and 3D information. In addition, ESRI's **ArcGIS Field Maps** (released in 2020) combines and replaces the older Collector, Navigator, Explorer and Tracker "apps" (i.e., applications) used for mobile workforce and mapping needs.

Yet another popular desktop application includes **Drone2Map**. One can use any modern drone to capture high-resolution imagery. Images can be processed in the field on a laptop to view in natural color, thermal infrared, or multiple spectral formats without the need for an internet connection. As a 2D and 3D photogrammetry app, Drone2Map lets you create georeferenced images and 3D point clouds, and then share them once you are connected to the internet. Its "sister" software is called **Site Scan**. This is a cloud-based app that provides a complete end-to-end drone mapping software from drone flight planning, pre-flight checklist, fleet management, process, analytics, and sharing. Unlimited amounts of drone flight data can be processed into 2D and 3D outputs through a Cloud environment. Because the data is in the Cloud, it is a lot more scalable; there is no need to publish or upload the data. It can be immediately accessed anywhere and by any device.

Since at least the year 2015, ESRI holds 43% of the market share in GIS software worldwide. This is more than any other vendor and will be the only referenced software within this text.

Autodesk, Inc.
Autodesk is a large and well-known publicly traded company with headquarters in San Rafael, California. It is best known for its AutoCAD family of products used worldwide. The company was founded over a quarter of a century ago, classically thought of as a successful CAD company that has since extended itself into GIS. Its purchase of MapGuide in the 1990's marked the start of internet GIS products, or server products, enabling data to be shared and maps published efficiently and inexpensively outside the user's organization. Autodesk's MapGuide worked directly with internet browsers and servers. (ESRI soon followed with their own web-based server.) AutoCAD Map 3D then became the engineering GIS platform, built to integrate GIS with CAD technology for helping users create, edit and manage geospatial data. It was a part of Autodesk MapGuide Enterprise, a proprietary software package enabling spatial data from Map 3D, as well as GIS databases, and raster formatted files to be accessed and distributed over the web. Today, the Autodesk family of products has evolved to offer InfraWorks and Civil 3D, which work with ESRI's family of evolved products to import, export, manipulate and publish GIS data. InfraWorks is a conceptual design software used to model and visualize infrastructure, primarily during the planning phase of a project. It can also create features from LiDAR point clouds and publish building models, right-of-way, watersheds and more to ArcGIS. Civil 3D is a civil engineering software used to develop intricate details during the design phase of a project. It can create terrain from point clouds. It can incorporate GIS topology rules. It can access multiple sources of spatial data from ArcGIS. These platforms, of course, appeal mainly to users whose focus is in CAD applications such as engineering, architecture and construction, but who want to incorporate geographic information and analyses into their projects.

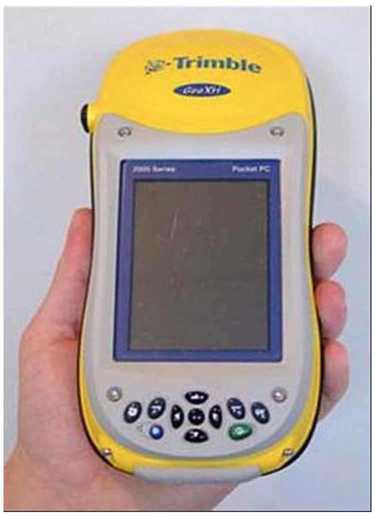
GPS PRODUCTS

Makers of recreational, mapping, and surveying grade GPS rover receiving units are many and growing. A few traditionalists include Leica, Lowrance, Trimble, and the more "household" names of Garmin, Magellan, and TomTom. Below are just two manufacturers representing the different grades of GPS rovers, as well as examples of their construction and surveying uses.

Trimble
Trimble was founded in 1978 in Silicon Valley, California. This also happened to be the year the first GPS satellite, the NAVSTAR, was launched. It is a publicly owned company with headquarters in Sunnyvale, CA. This company manufactures mapping and survey-grade GPS units for use in surveying, construction, agriculture and fleet management. Rover and base station receivers are sold with powerful antennae for post-processed surveying. Rover units are used in construction on bulldozers, backhoes and excavators for improved grade control.

They are also used to increase paving accuracy and smoothness on highway jobs when installed on paving and milling machines. GPS units are used in precision agriculture for controlling drainage grading (minimizing ponding) in fields, thus improving crop yields.

Pest and fertilizer application rates are also controlled using precise machine guidance at night or through dusty conditions to avoid overlaps. Logistics companies such as FedEx, use GPS units to track the location of trucks and the timing of deliveries as a means of ensuring the quality of their service.



Traditional mapping grade receiver

Survey grade GPS antenna mounted on tripod over a geodetic survey mark
Source: NOAA

Backpack mounted GPS roving antenna and receiver unit
Source: NOAA

Garmin, Ltd.
Garmin was founded in 1989 by a small group of engineers. It is a publicly owned company with its American headquarters in Olathe, Kansas. It caters primarily to the consumer recreation market. The company offers automotive products (the GPS units used for navigation inside vehicles) and fitness devices, along with outdoor handheld products for hikers and geocachers. Handheld devices include those with mapping, camera, two-way radio, and even dog-tracking capabilities (software sold separately). Garmin offers a series of marine products such as sonar locators for fish finding, and navigation units for tracking the bearing, course and speed of other boats in avoiding collisions.

Recreational grade receivers
Source: USGS

GNSS mapping grade receiver
for use with tablet or smart phone

Consider your objectives when purchasing GPS roving receivers for data collection. What data are you collecting and where? How accurate do your locations need to be? Make sure you understand the software that you purchase with the rover unit, or with the antenna to run in the background of your smart phone or tablet application. Remember, your GPS coordinates are captured in WGS84. They will be projected into the coordinate system of your base map service, which may or may not be the coordinate system of your office maps. You may want to purchase field software with this capability. Some clients prefer location coordinates tied to the NAD83 datum, for instance. In certain circumstances, location data can best be verified in the office when collecting coordinates is time-consuming due to multi-path errors, or if weather conditions would otherwise delay personnel operations.

DATA FORMATS AND REPOSITORIES

Data collected through static or real-time kinematic surveys using the Geographic Positioning System is processed for use within computer-aided design (CAD) software that designers can use or for use as an imagery layer within a GIS for further analysis and mapping. In the former case, survey files arrive at the office for post-processing which includes correcting coordinates, removing anomalies such as irregular contours, adding breaklines, or putting features on different levels of a CAD file. For example, Bentley's MicroStation is a CAD software used by state departments of transportation. It includes an extension called Geopak that accepts survey files for post-processing and conversion to a useful 3-dimensional design file called a Digital Elevation Model or Digital Terrain Model. This model is used by civil engineers to design alignments, cut cross-sections, and determine earthwork quantities needed in constructing roadways. In the latter case, LiDAR images collected are assembled into an elevation raster layer that can be viewed in different spectral ranges or sun azimuths. These different views can be used by scientists or planners, for example, to locate vegetation types, water features, or to look around overhanging features.

Drawing Exchange Format (DXF)
Data generated from GPS survey receivers include *DXF* files. This format was developed by Autodesk to be interoperable with non-CAD software packages. DXF files can be viewed, edited, and exported with AutoCAD software. They can also be imported into a CAD file from a UAV-generated file. The wide range of capabilities makes DXFs incredibly useful in several industry applications and especially when it comes to computing earthwork quantities.

Laser (LAS) Data Exchange files
Remote sensing data generated from the use of LiDAR data collectors include Laser Data Exchange formatted files or *LAS* files. The LAS file format (**.las**) is a binary and public file format containing light pulse returns from the ground or objects recorded as points with positions and heights. It was developed primarily for the exchange of LiDAR point cloud data, sometimes referred to as 3D vector data. ArcGIS supports LiDAR data that is provided in the LAS file format. Other proprietary formats exist.

GIS files come in many different formats, some of which you may recognize. In fact, several files can make up one layer's file in a GIS. That's because, as mentioned above, a GIS feature layer has geometry, attribute, behavior, and often georeferencing information associated with it. Raster layers can have attributes and likely, georeferencing information. Each of these components provide information within separate files and folders in Windows Explorer or other file management systems. Data sources include the following:

- Raster datasets (raster layers): images, DEMs and GRIDs
- Vector datasets (feature layers): shapefiles and CAD files
- Tabular datasets: dBASE and INFO
- Geodatabases
- Triangulated Irregular Network datasets: TINs

Each dataset has their own format and unique file extensions associated with the company that produced them. Some of the more popular datasets and properties are introduced below. Graphical illustrations of some of these files and their management follow the introductions.

Images
Images captured using satellites and unmanned aerial vehicles (UAVs) can be georeferenced and manipulated for use in a geographical information system. These systems can display images as

rasters in many different formats. Common raster formats include: GeoTIFF, MrSID, and IMG. GeoTIFF is a public domain data standard allowing georeferencing information to be embedded within the popular Tagged Image File Format (**.tiff**) files. GeoTIFFs files are commonly used to store satellite and aerial imagery data, along with geographic metadata that describes the location in space of the image. This file format is compatible with nearly all CAD and GIS applications. Aerial photography and other images can be viewed and edited as MrSID (**.sid**) files by LizardTech, Inc. and IMAGINE (**.img**) files by ERDAS, Inc. These companies provide image compression and manipulation software to allow the user to create vivid, seamless georeferenced images for use in a GIS. USGS topographic maps are often viewed in a GIS in a Digital Raster Graphic (DRG) format. The USGS created these digital image maps by scanning the paper maps at 250 and 500 dpi and saving them as GeoTIFF files. The newer "US Topo" digital image topographic maps, created from layers of geographic data, are intended to replace the scanned digital raster graphics, though not intended to be used in a GIS. These files are constructed in stand-alone georeferenced portable document format (GeoPDF). To discover more about these maps, visit https://www.usgs.gov/faqs/what-geopdfr.

Whether optical or digital photography-based aerial images, are frequently used in a geographical information system. Long before GIS, aerial photographs were used by photogrammetrists to scale and measure objects on the ground. As with other layers, images must be georeferenced inside a GIS. Additionally, there are distortions that occur with cameras and terrain relief, which must be corrected. The process of georeferencing and correcting aerial photos such that the scale is uniform throughout the image is called *orthorectification*. These computer-generated images of photographs are used just like a map to make measurements. Digital orthophoto quadrangles, or **DOQs**, are a product of the USGS, and were arguably the most popular orthorectified images in use. (Their popularity could be due to the fact that other orthorectified images are often erroneously referred to as "DOQs".) Each image covers an area either 3.75 minutes x 3.75 minutes or 7.5 minutes x 7.5 minutes in longitude and latitude quadrangles.

High Resolution Orthoimagery (2008, 2010, and 2012) of the Hoover Dam Bypass Project

Source: USGS

DEMs
Another frequently used raster is the digital elevation model, or DEM. Elevation measurements (*z*) are interpolated across an area to create a 3-dimensional surface for terrain simulations. Photogrammetric processing software integrated with drone data collection apps can also yield DEMs. Each cell of the raster holds an elevation value. Orthophotos are routinely corrected for variations in terrain using a DEM. DEMs can be representative of the ground, water, trees, buildings, or other objects with height. They can alternatively, be representative of only the bare-earth and water bodies. Terrain modeling is used for a plethora of science and engineering applications, including stream extractions for headwater determinations, floodplain mapping, erosion modeling, power or gas transmission line routing, pollutant loading/water quality modeling, etc. The terrain raster layer figure presented earlier, is an example of a digital elevation model. In drone mapping workflows, GeoTIFFs can contain both orthophotos and DEMs.

GRIDS
GRIDS are an ESRI developed raster format. Their cell values are numeric and are either of integer or floating point type. A GRID file does not have an individual file extension. It is stored as a separate directory with associated files and tables that contain specific information about the grid. The directory name is the GRID name. Digital elevation models are often in GRID raster format. Former ESRI architecture used a proprietary program called "INFO database" to store and manipulate attributes of a GIS dataset. GRIDS may have a default attribute table called the *value attribute table* (VAT). This is an INFO table with at least two fields: "VALUE" and "COUNT". The VALUE field stores a value for each unique cell within the raster. The COUNT field stores the number of cells for each value. For instance, a land use grid's VAT can report the number of cells for each land use classification.

Shapefiles
Shapefiles originated with older versions of ESRI software but are still widely used today. They are a simple and versatile format for storing the geometric location and attribute information of vector features. They do not store topology information. They can be edited. The shapefile format defines the geometry and attributes of geographically referenced features in three or more files with specific file extensions that are stored in the same project directory, or file system workspace. They each possess the same prefix name but must include a **.shp** extension (the main file that stores the feature geometry), a **.shx** extension (the file that stores the index of the feature geometry), and a **.dbf** extension (the dBASE table that stores attribute information of the features). The dBASE table format is a proprietary database program used, in part, to create tables for use with ESRI shapefiles. A workspace holding shapefiles and associated dBASE tables can be joined to that shapefile's features.

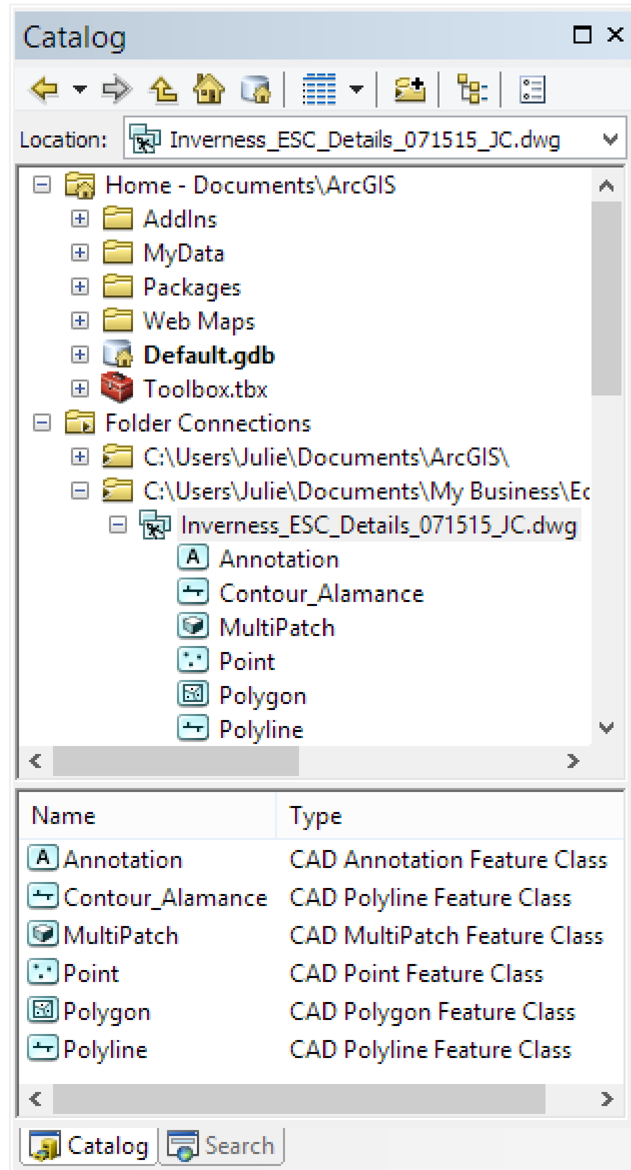
Another file format that may or may not accompany a shapefile possesses the **.prj** extension. A file with this extension holds the projection information and is used by ESRI's ArcGIS. Ground coordinates with which to georeference vector datasets are specified in the lower left corner of the layer. A couple of other optional file formats you might see accompanying the three or four above in the same project directory include **.sbn** and **.sbx**. Files with this extension store additional spatial indexes of the features in the shapefile to speed spatial queries and renderings.

CAD Files

Once terrain and objects are surveyed and a design file is prepared for use in a CAD software, multiple file formats can then be imported into a GIS for further editing or analysis. In ArcGIS, CAD file formats supported include: .dwg, .dxf and .dgn. Geometric elements and entities such as lines, arcs and polylines, along with ellipses, shapes and solids are supported as CAD polyline and CAD polygon feature classes, respectively within ArcGIS. Text is typically imported as an annotation feature class. Point feature classes may also be created and may include insertion points from CAD drawings. Upon importing, all feature classes are automatically contained in what is called a *CAD dataset*. It is advised to request all reference files associated with the CAD drawing for use in ESRI's ArcMap. When imported, each feature class created represents all features of the same type from all CAD layers/levels. For example, the polygon feature class represents all shapes, solids, etc. within the CAD file and their attributes. Only entities in the model space are viewable in ArcGIS for Desktop or ArcGIS Pro.

It is important to note that CAD coordinate system and world file transformation information within ArcGIS are stored in separate text files with extensions, **.prj** and **.wld**, respectively. AutoCAD .dwg files are the exception, and may contain a coordinate system embedded in the drawing. All CAD feature classes imported together share the same spatial reference and are read-only but can be used as input to new features created through geoprocessing tools within the GIS.

The importing and conversion process of CAD entities or elements to GIS features is not always an error-free process. Commonly reported problems include CAD data not being georeferenced (.prj and .wld files absent), specialty entities/elements such as arcs or ellipses not easily converted into features, under- or over-shoots from poor drafting that make the data unusable for creating topology without correction, and last but not least, importing CAD annotation. Fortunately, ESRI's support website http://support.esri.com/en/ offers solutions to most of these problems. Additionally, the company employs a CAD team to address such issues.



CAD dataset in (Arc)Catalog

Geodatabases

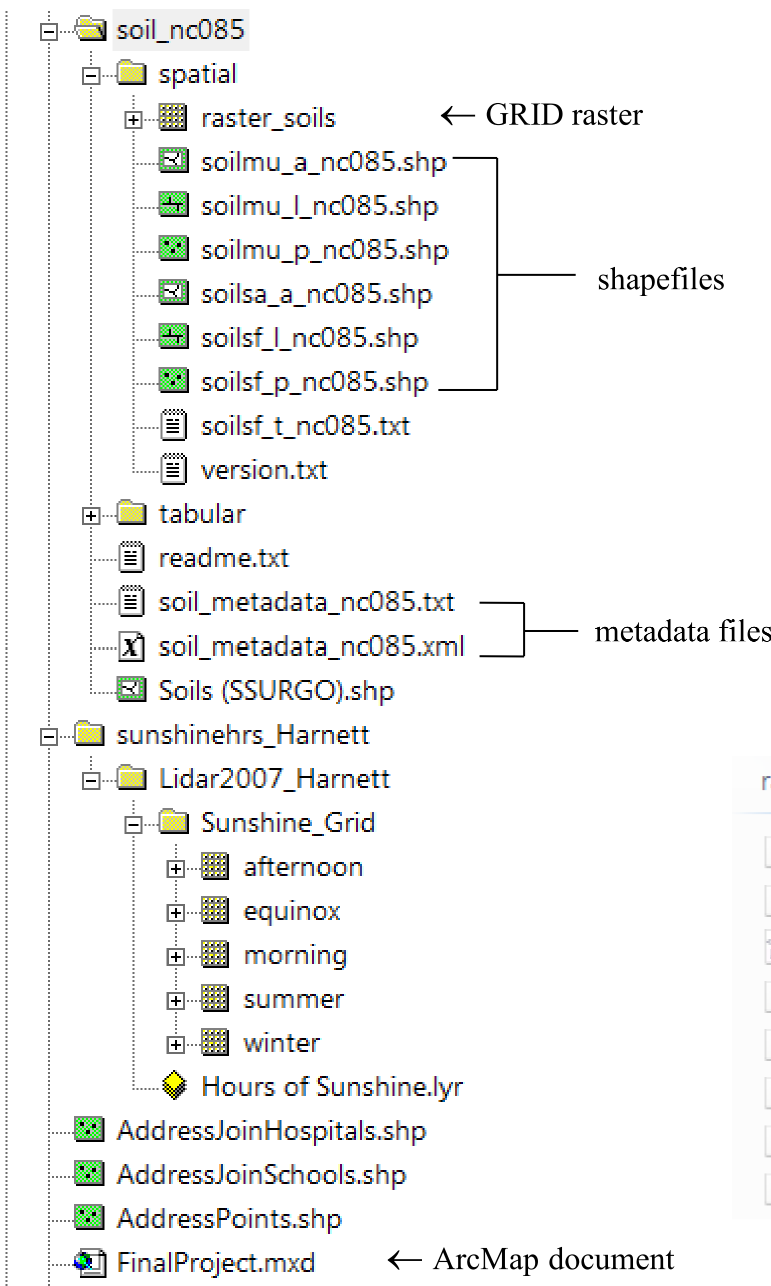
The *geodatabase* concept was introduced with ESRI's ArcGIS for Desktop. It is a workspace for holding vector, raster, CAD and other datasets, and tying together spatial features with attributes. Geometry and attributes are maintained in a single table per feature class. It also provides a common *spatial reference* system for feature classes (remember points, lines, polygons). Different types of geodatabases exist, each distinguished by the number of supporting editors, data storage formats, and size limits.

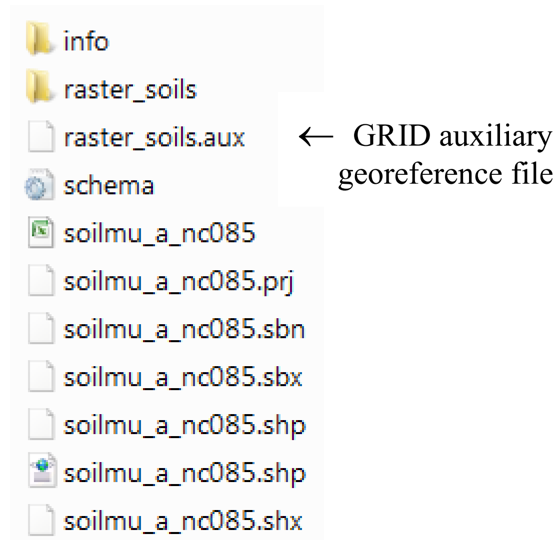
TINs

Triangulated Irregular Network files, or TIN files, are a form of vector data used to simulate terrain surfaces from given elevation points. They are constructed by triangulating a dataset of points (vertices) through an interpolation method. The vertices are connected by edges to form a network of triangles. TINs are typically used for high-precision, engineering modeling of smaller areas, where they are used to calculate planimetric area and volume and can be used to calculate surface area. Contours can be generated, and cross-sections can be cut from TINs using CAD software alone. A TIN model is desirable over raster DEMs when it comes to modifying elevation surfaces for designs. TINs do require well-defined, survey breaklines. Breaklines represent an abrupt change in elevation and must follow one edge of a triangle in the file. Examples include the crown of a roadway, retaining walls, dams, ridges, or stream bottoms. A TIN is stored as a directory of files. A TIN directory/workspace (folder) contains a minimum of seven **.adf** formatted files containing information about the surface. These files are encoded in binary format and are not readable by standard text display or editing programs. In a similar file structure to GRIDs, projection information for a TIN file is stored in a **prj.adf** file within the TIN folder.

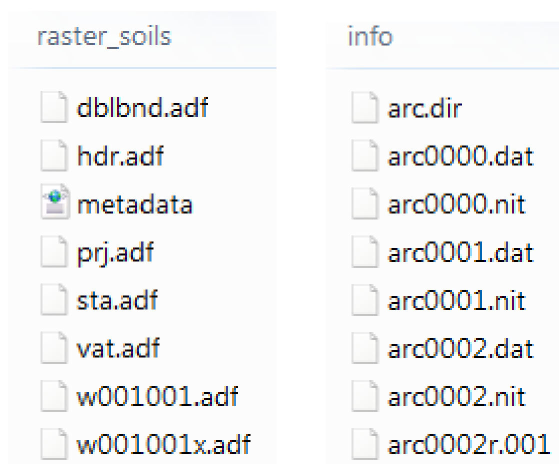
After all of this discussion about file formats, it is important to note that if you are working within ArcGIS for Desktop or Pro (and likely others), your file contents will appear differently than they do in Windows Explorer. When managing files with these system architectures, each of the dataset's supporting feature, georeference, topology, and/or index files are displayed as one layer with or without a defining icon beside the file name and in a hierarchy tree. With shapefiles and geodatabases, you may also see database attribute tables within their directories. Files should always be managed within the GIS system being used, and not with your computer's operating system file manager. GIS file manager applications preserve the link between individual supporting files that are otherwise seen as independent files outside of a GIS. If you delete a .shx file or an INFO folder while in Windows Explorer for example, your shapefile or raster will be corrupted.

Below are examples of GIS files as shown in ArcGIS ArcCatalog (left) and in Windows Explorer (right).





GRID folders and shapefiles as seen in Windows Explorer



INFO database files as seen in Windows Explorer

METADATA

Metadata is data about data. In better words, it is documentation for your dataset. Why is documentation needed? A metadata file provides identifying properties such as attribute information of features, raster resolution, data extent, coordinate system information, the author, and origination and revision dates of the data. Documenting these properties can assist in deciding if the data you've spent time searching for meets your needs or already exists. More descriptive metadata may explain how the data was collected or derived, its accuracy, and the quality control measures taken when edited.

The more standardized the structure and content of the documentation, the more effectively it can be used by both people and computers. A metadata standard is simply a common set of definitions that are presented in a structured format. There are a number of standards from which to choose. **The Federal Geographic Data Committee's Content Standard for Digital Geospatial Metadata** is the current U. S. Federal Metadata Standard. This is a very detailed standard that aims to provide complete documentation of a data source. According to Executive Order 12096, all Federal agencies are ordered to use this standard to document geospatial data created as of January 1995. The standard has been implemented beyond the federal level with State and local governments adopting the metadata standard, as well.

The International Organization of Standards also develops content standards for geographic information metadata, including the **North American Profile ISO standard 19115(-2)**, which provides for XML storage of documentation. Extensible markup language (XML) is a set of rules for creating standard information formats, transferring both the format and data across computer applications. (It is a compliment to HTML, or Hypertext Markup Language, a standard used to create web pages for publication on the internet.) The number, type, order and grouping of elements or objects (such as tables or views in a database) allowed in an **.xml** document are described in the schema, or document structure.
The ISO standard 19115 also allows for detailed documentation but requires only a few elements and offers several optional ones. It was formally adopted by the American National Standards Institute (ANSI) in June of 2009.

As with coordinate systems, metadata is usually edited according to a predetermined client or government, standards-compliant format.

GLOSSARY

Attribute – The general name given to features within a database. Attribute values are the specific quantity or quality assigned to attributes, whether text or numeric, used to describe their properties.

***DEM* –** Digital Elevation Model. A surface model providing elevations of terrain or surfaces. Each cell in the raster holds an elevation value, usually at a fixed grid interval.

DGPS – Differential Global Positioning System. Ground-based augmentation system requiring two or more receivers. Used to correct position coordinates. See definition for *GPS* below.

DOQ – Digital Orthophoto Quadrangle. An image that looks like an aerial photograph, but that has had distortions caused by camera tilt and topography removed. Such orthorectified images have been georeferenced and are capable of being used as a map.

DRG – Digital Raster Graphic. Raster format files that are digital representations of USGS topographic maps that have been scanned and georeferenced to the Universal Transverse Mercator projection.

DTM – See Digital Elevation Model. Sometimes these terms are interchanged. Other times they may be distinguished by the type or class of points being returned from a scanner.

***Feature* –** A point, line or polygon chosen to represent a real-world object. In a GIS, features possess geometry, attributes, and topology.

Feature class – Homogeneous collections of common features with common attributes and a shared spatial reference. All features within a point feature class for instance, share common attributes (e. g. Name or Elevation table headings) and a shared spatial reference.

***Feature dataset* –** A collection of feature classes within a geodatabase that share the same spatial reference and user-specified relationships, such as topology rules.

Geodatabase – A database containing geographic datasets for a particular area and subject. Datasets contained within a geodatabase share a common spatial reference system.

Geoprocess – An operation performed on geographic, or spatial, data such as buffering, overlays, and spatial queries that result in new data.

Georeference – The process of assigning geographic coordinates to an image or to features.

Geospatial data – Data that has been referenced to a geographic coordinate system in order to conduct spatially related analyses.

GIS – Geographical Information Science/Systems. The science deals with the study of spatial and earth-referenced data and their relationships. A system is designed to capture, query, analyze, manipulate, store and present all types of geographically referenced data. It consists of geographic data, procedures, software, hardware, and personnel. These components are needed to perform GIS functions.

GNSS – Global Navigation Satellite System. The GPS is the primary navigational satellite system in the United States.

GPS – Global Positioning System. A global navigation satellite system developed by the United States Department of Defense for precise navigation of nuclear weapons and for defense mapping. The constellation of satellites was formerly named NAVSTAR-GPS before being shortened. In civilian talk, a "GPS" is a mobile receiver unit used to navigate by capturing and identifying locations with coordinates.

GRID – An ESRI format for displaying non-imagery rasters within a GIS.

LiDAR – Light Detection and Ranging. A type of remote sensing using light waves transmitted from aircraft-mounted sensors to detect the height of objects on the ground, or the ground itself.

Map Projection – A set of mathematical equations used to transform spherical coordinates into a planar coordinate system. Projections are classified primarily as either planar, cylindrical, or conic.

Metadata – Documentation about data or datasets. This includes properties such as attributes of features, raster resolution, data boundaries, coordinate system information, accuracy, the author, and origination and revision dates of the data.

Raster layer – A format for representing and storing discrete and continuous data. Images and ESRI GRIDs are examples of raster datasets represented as layers in a GIS.

Remote sensing - Remote sensing is the measurement of physical, chemical and biological properties of objects without direct contact.

SBAS – Satellite Based Augmentation System. A means of processing or correcting position coordinates using satellites in conjunction with ground receivers.

Shapefile – A file format created by ESRI used to store geometric and attribute information for vector features.

Spatial Reference - A coordinate system (including projection) with domain extents.

TIN – Triangulated Irregular Network. A vector dataset created from elevation measurements used to simulate terrain surfaces for measuring and modeling.

Topology – The rules of behavior associated with or between vector features in spatial relation to each other.

Vector layer – A format for representing and storing discrete data. Shapefiles and TINs are examples of vector datasets represented as layers in a GIS.