A SunCam online continuing education course

Introduction to GIS and GPS for Engineers and Surveyors

by

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PURPOSE

The purpose of this course is to provide a basic understanding of the term "GIS", and how this science is applied in engineering. It is meant to familiarize engineers and 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. Engineers should be able to recognize topographic and other GIS file types presented to them by clients for use on their projects. 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 engineers and surveyors to GIS and GPS concepts and terminology
- Explain the role of GIS in engineering applications
- Familiarize readers with GIS file formats
- Discuss current GIS and GPS products, along with their uses

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

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 period 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 engineering 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 now engineering.

Another evolution in the communications world was occurring during the same time period. The United States Department of Defense 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.

During the 1990's, web-based servers allowed the publication of dynamic maps and GIS data to be shared by businesses, local governments and other organizations, both locally and to the public over the internet. The internet has also allowed GIS users to cost-effectively link off-site users together (e. g. customers and suppliers, telecommuters and office workers, students and teachers). Likewise, geographical information science has turned out to be such an intriguing, as well as beneficial field, that it has encouraged many people to take advantage of the internet. 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 traditional method 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 as viewed from within Microsoft Edge

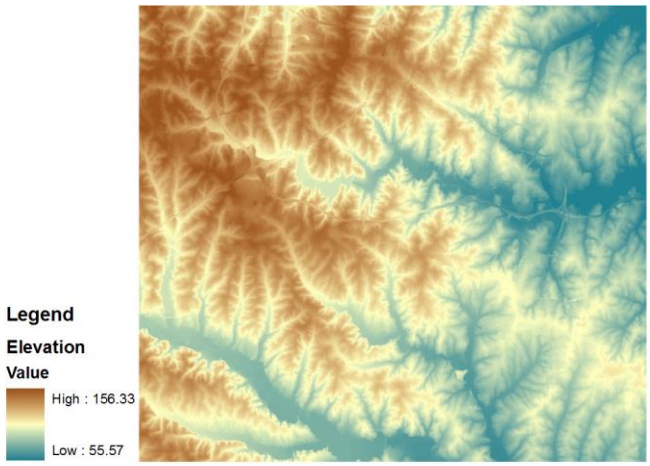
Throughout this course, we will introduce the functions of a GIS, explain the components of vector geographic or spatial data, discuss real-world engineering applications of GIS, and discuss the importance of referencing data to a coordinate system so that it can be analyzed and modeled with meaning. Multiple GIS software will be discussed, followed by the file and database formats available for manipulation and storage. Methods of capturing data, including the use of GPS and its products, 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.

FUNCTIONS OF A GIS

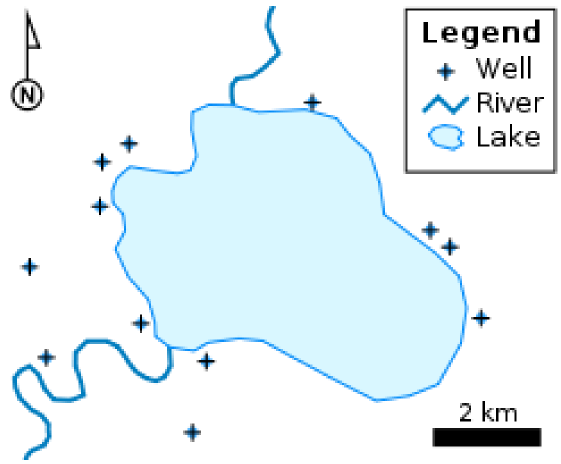
A Geographical Information System is powerful in that it provides many functions for finding real-world solutions to problems using provided data. Below are six functions of most systems:

1) Capturing Data - The ability to capture geographic (coordinate) and tabular (attribute) data using various means is what makes the System versatile. We will cover some of these means towards the end of the text.

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 contain more detail with an increased cell count per unit area. The level of detail is more accurately termed the *spatial resolution* of the raster, and depends upon the device used to capture the image. Rasters will be discussed further within the text.

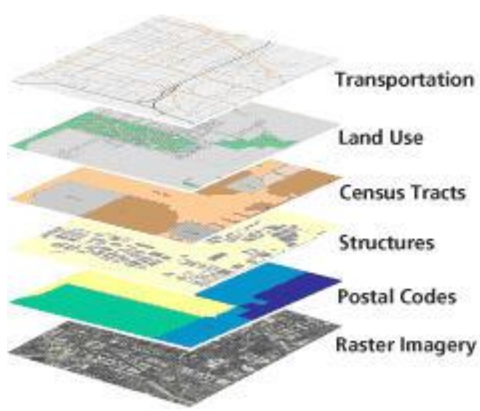


Raster layer of terrain relief



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.

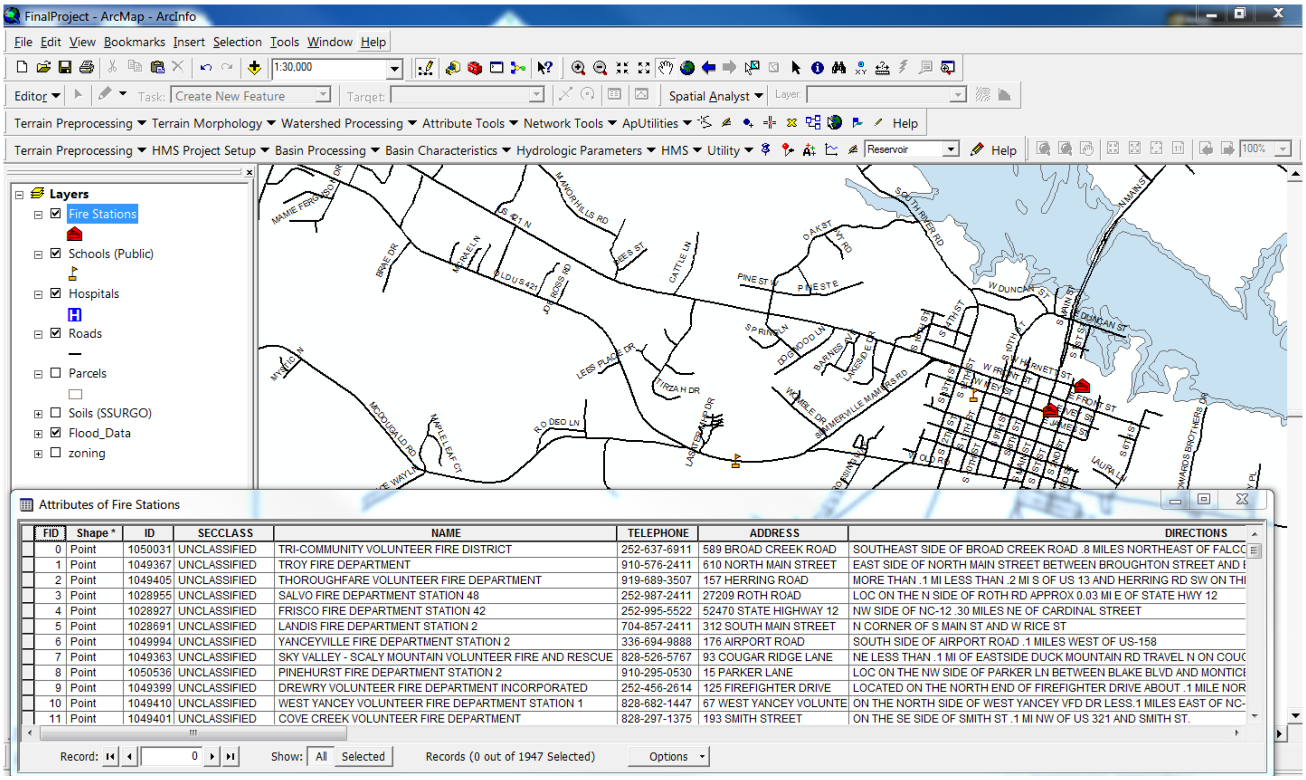
5) Displaying Data – A GIS must have an interface and graphics capable of displaying results at different scales and with multiple symbology. It can often simulate 3-D images from 2-D images using shading techniques. A GIS is capable of 3-D modeling when a third, and often fourth dimension, is provided.

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

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.

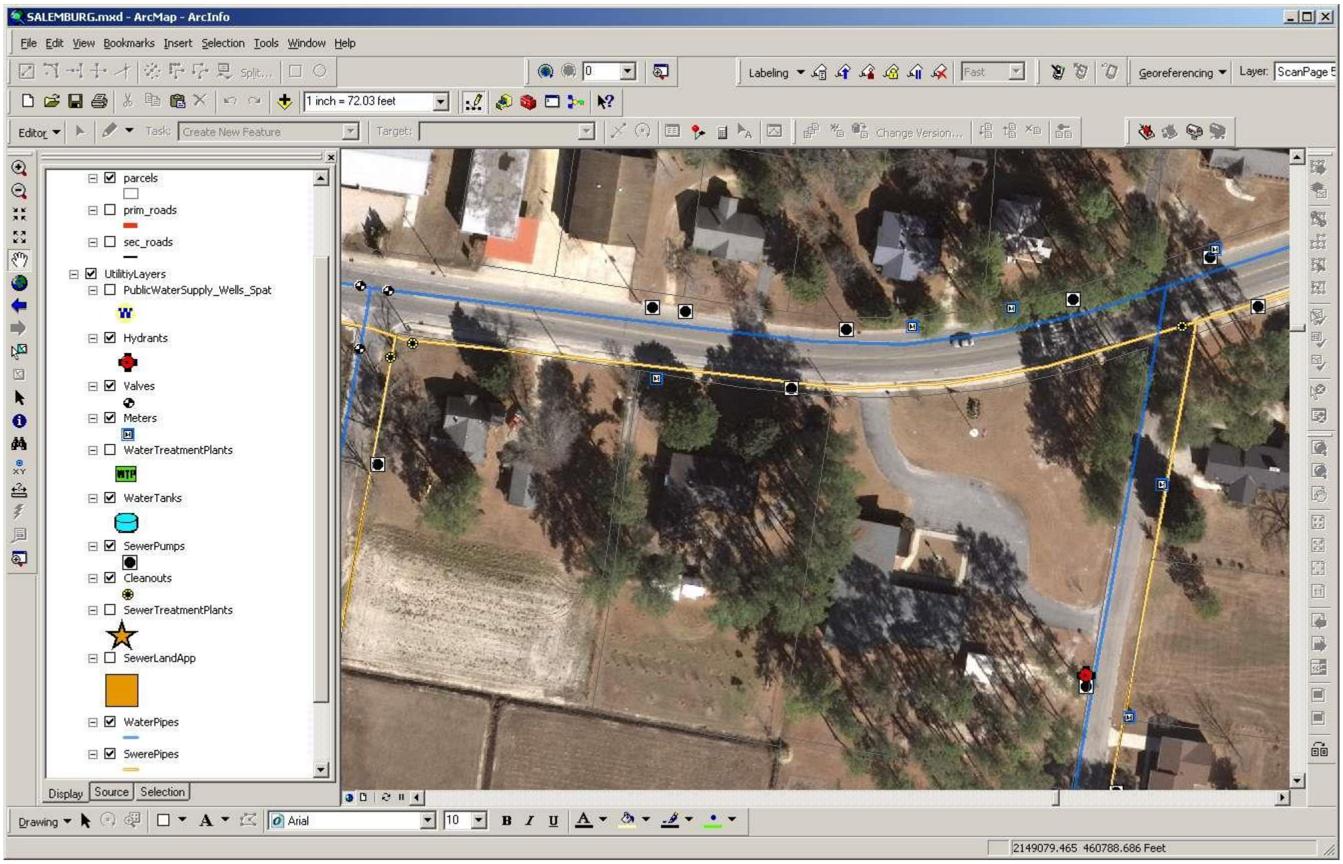
A typical behavior is that these areas cannot overlap one another. Line features such as interstates may have a rule prohibiting them from intersecting city streets.



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.

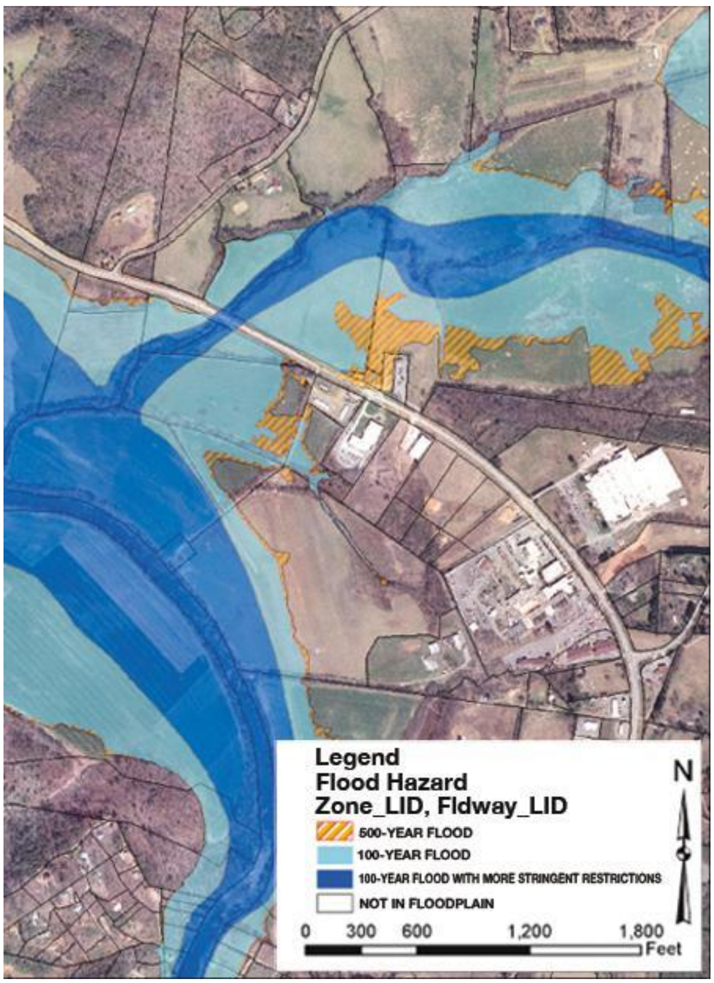
APPLICATIONS FOR ENGINEERS

Geographical information systems are fundamentally about problem solving – and so is engineering. While the application started out primarily for the military and scientific communities, civilian engineers have learned to integrate spatial analyses and geoprocessing into their workflows to increase accuracies, visualization, and productivity. The utilities sector relies heavily upon GIS to map layouts and provide inventories of oil and gas pipelines, water/storm water/storm sewer pipe networks, and electric lines and transformers. Petroleum, hydraulic, sanitary sewer, and electrical engineers use GIS to manage databases of their networks, and to query and pinpoint potential problems within systems.



A utility map within a GIS showing water and sewer lines, valves, sewer pumps, and fire hydrants
Notice the table of contents listing each layer to the left.
Source: Mr. James Perry, Lumber River Council of Governments, NC

Using terrain and land use data, electrical or nuclear engineers can compute the least costly path for construction of a new power transmission line. Transportation engineers use GIS to map and inventory roads and bicycle paths, as well as to plan new routes. Traffic engineers use GIS to analyze accident locations along routes and frequencies at intersections. They may also develop evacuation vulnerability maps for hurricanes or fires, based upon population densities and street ingress and egress. Chemical engineers use GIS to plan for toxic chemical spills. They may model scenarios for the location and extent of liquid and/or gaseous spills from truck accidents or train derailments using population distributions and buffer areas (people living within a certain distance of the accident). A GIS can assist in hydrologic analyses through automated watershed delineations, in measuring incremental distances used to compute flow time of concentrations, and in estimating storm runoff distributions across a heterogeneous watershed(s). Hydraulic or water resource engineers also use GIS to help automate the tedious process of terrain processing for use in bridge and floodplain modeling.



A floodplain map created using a GIS

Environmental engineers and land use planners use GIS to model pollutant loads across a heterogeneous watershed(s) for tackling water quality issues. Agricultural engineers use GIS to model erosion and map problem areas based upon soil, harvest cycles, and rainfall data.

A GIS community responds to 9/11 attacks

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When we memorialize the anniversary of the September 11th attacks, we also reflect on how the GIS community responded during those hectic few days following the disaster.

The New York City Emergency Operations Center (EOC) was originally located in 7 World Trade Center. Working from a copied base map and out of a temporary EOC, GIS officials with the New York City Office of Emergency Management (OEM) worked with the NYFD to recover data and produce maps of building footprints, utility outages, subway station and road closures needed by emergency responders. This information aided in the search and reconstruction efforts, including pinpointing damaged water valves and routing debris removal. It also aided newscasters, commuters, and modelers of surface dust monitoring.

Meanwhile, federal agencies began withdrawing public geospatial data from their websites for fear that specifics such as risk management plans for the nation's chemical and nuclear plants might aid terrorists. A study by the National Geospatial-Intelligence Agency (formerly, the US Defense Mapping Agency) and the USGS determined a lack of sensitivity of public data on websites, and it was quickly restored. Nevertheless, some government bodies have opted to intentionally remove data or "blur" portions of images they deem sensitive.

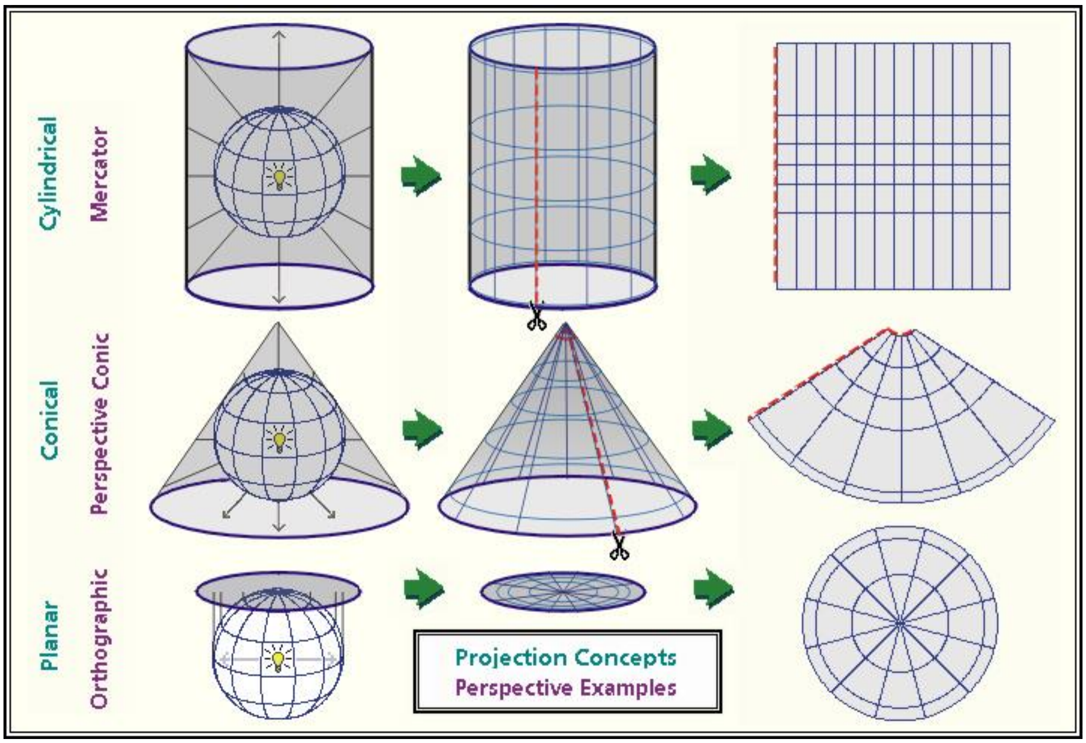
Last but not least, computer engineers with experience in programming, and server and enterprise database administration are in large demand to setup client-server platforms and write scripts for customizing GIS tools and user interfaces.

These are just a few examples of powerful engineering applications within a geographical information system. The use of a GIS to map, measure, model, or manage data is also used in transportation logistics, real-estate markets, tax assessments, insurance, search and rescue operations, intelligence gathering, and counter-terrorism security measures, each across private sector, military markets, and all levels of government. Employment for Geographical Information Science Professionals, or GISPs (see Glossary for definition) working in government is typically the largest at the county and municipal levels. The largest overall employers are consultants and vendors, employing over one-third of all registered GISPs.

GEOREFERENCING, COORDINATE SYSTEMS AND MAP PROJECTIONS

Users of a GIS 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.



Types of Projections
Source: University of California, Santa Barbara

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 coordinate system is the **State Plane Coordinate System** with 125 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 and civil engineers are familiar with datums. Horizontal datums have been defined either by classical terrestrial surveying methods measuring distances and angles or by an ellipsoid and its position relative to the earth. Thus, 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 1983 (NAD83)** (earth-centered)
  with the **Geodetic Reference System of 1980 (GRS80)** ellipsoid
  Over the years, there have been a number of realizations of this datum based on improvements in global navigation satellite system observations. 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. The WGS84 currently uses the WGS84 ellipsoid developed by the United States Department of Defense and the International Terrestrial Reference Frame (ITRF), 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.

- **North American Terrestrial Reference Frame of 2022 (NATRF2022)**
  with the latest **GRS80** ellipsoid. This system will soon replace the NAD83 horizontal datum for which the origin of its reference ellipsoid has since been discovered to be offset by about 2.24 meters from the true center of the earth. Due in part to recognition that the earth's continents are not fixed, this system is designed to account for a predicted drift of the North American tectonic plate over time. It will be aligned to the ITRF whose origin is earth-centered; it differs however, from this ideal international frame in that a more "localized" North American continental frame was chosen – one of four such reference frames used across the globe that drift in different directions. Location coordinates between the latest NAD83 realization and the new datum are expected to differ anywhere from 0.5 to 2 meters across North America. The NATRF2022 will rely primarily on global navigation satellite systems such as the U. S. *Global Positioning System* which measures time while monitoring the movement of our reference stations. It is thus, a plate-fixed, time-dependent system which no longer relies upon physical survey monuments that are not as fixed as we once thought and which deteriorate with time. The State Plane Coordinate System (SPCS) as we know it will also be redefined to be compatible with the new reference frame. The SPCS2022, as abbreviated, will be the official projected coordinate system for our national spatial reference system. As of this writing, the NATRF2022 is experiencing a delayed release.

Datums allow for planar coordinates to be calculated when applying a projection to an area.

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

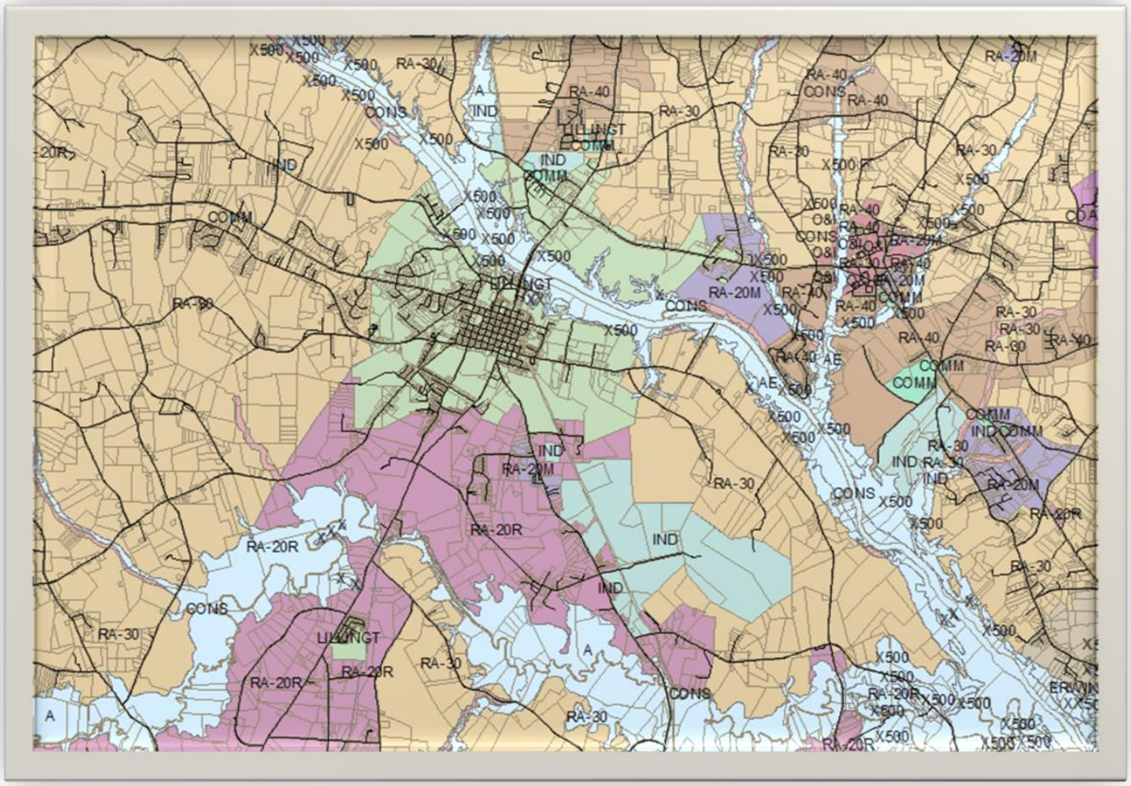
according to the coordinate system in which you are working (e. g., Northing/Easting or Latitude/Longitude). In some Systems, the default option automatically sets to the extent of your geographically most expansive input layer.

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 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.

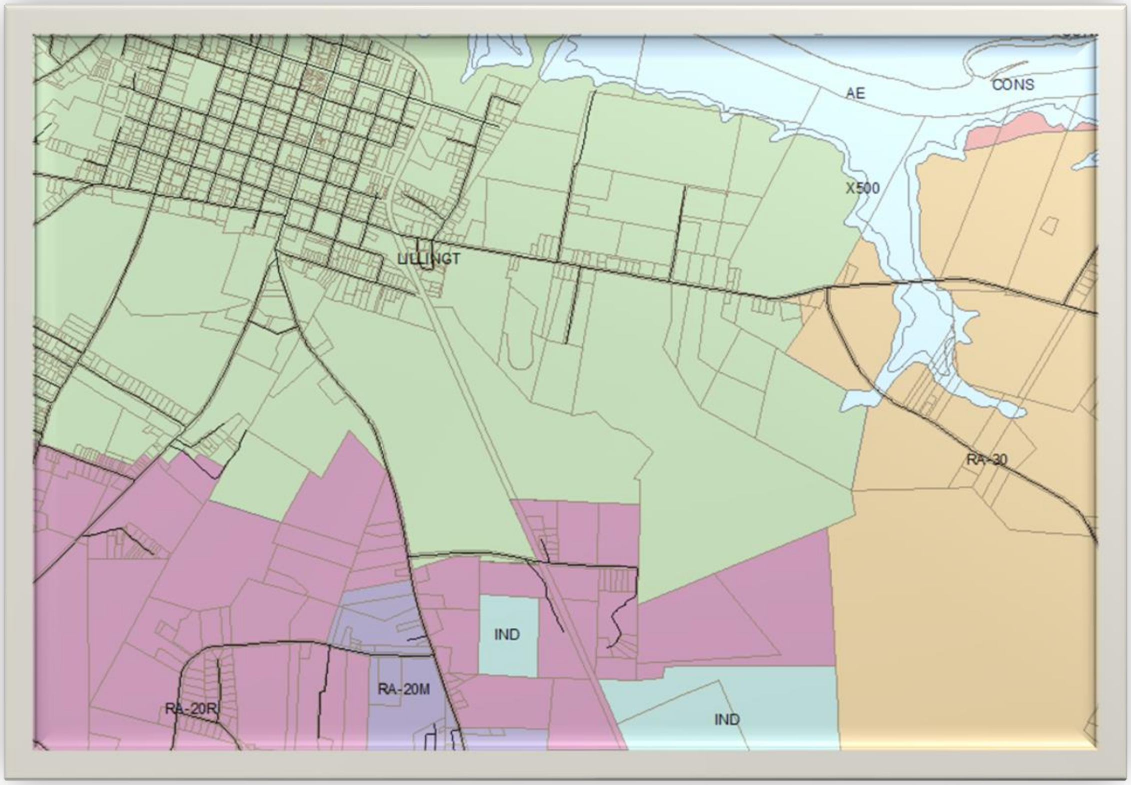
Unique to some geographical information systems is the ability to set a minimum scale at which certain layers are displayed. This prevents clutter on your map by restricting the display of features until a more appropriate scale is reached. As you zoom from a small to a large-scale map, more features 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

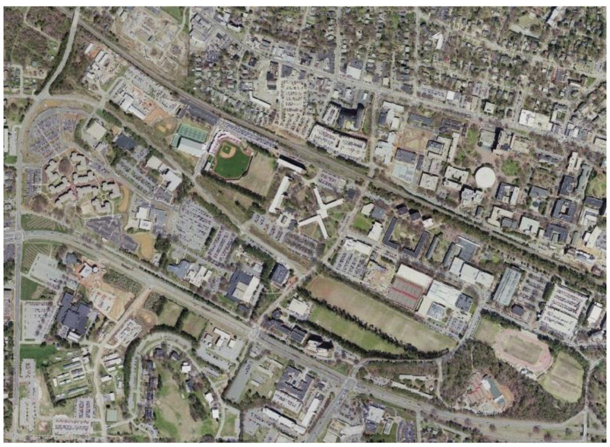
At a scale of 1:100,000, the map above would be easier to read once the parcel data and labels have been removed. A title would be appropriate to define the area of interest, accompanied by a legend to distinguish zones. The viewer can get a general sense of the type and limits of development within 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 rasters, 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. Rasters deal with resolution in terms of cell size. 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, access to Cloud servers, portable memory devices, 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, raster data 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 your level of detail, and can lead to a blurred or pixilated view of low-resolution rasters. Whereas at larger scales, high-resolution rasters 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 typically 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.

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 and ArcCatalog file management tool, is the last of the supported desktop versions of this family of products and is scheduled to be retired on 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** 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 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 much 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 also 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.

DATA FORMATS AND REPOSITORIES

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

Geographical information systems can display images captured from satellites and unmanned aerial vehicles (UAVs) 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 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, for the most part replaced the scanned digital raster graphics, though are 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 map images, visit https://www.usgs.gov/faqs/what-geopdfr.

Aerial images, whether optical or digital photography-based, are frequently used in a geographical information system. Long before the science of geography, 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 are 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. DOQs are incorporated into a geographical information system for displaying and revising digital planimetric data, for detecting changes in landscapes over time, and for assessing soil erosion, to name a few. USGS DOQs are distributed in GeoTIFF format. The utility and floodplain map figures presented earlier, include orthophotos in the background. As shown below, this orthoimagery was used to monitor the progress of construction on the Mike O'Callaghan-Pat Tillman Memorial Bridge which has separated tourist traffic from all other traffic over the Hoover Dam since the year 2010.

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

Raster image datasets contain partial georeference information in "world files". These files contain ground coordinates of the upper left pixel of the image, scale and rotation information. They are identified by their file extension. The world file will have the same name as the image file and a file extension that is based on the first and last letters of the image's file extension plus the letter "w". Thus, MrSID world files have the **.sdw** extension. GeoTIFF world files are recognized by the **.tfw** extension. USGS DRG standards use the UTM Projection system with a .tfw associated file in being georeferenced to the earth. World files are simple text files that can be created outside a GIS by the user or written for you when exporting from a GIS to another application. When you download a raster, you may also notice an accompanying file(s) with the same name as your image, except it may have an **.aux** file extension. This auxiliary file may store information that cannot be stored internally with your raster, such as projection information or the coordinate system itself. It would be downloaded and stored in the same directory as your image file.

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 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 or water quality modeling, etc. The raster layer of terrain figure presented earlier, is an example of a digital elevation model. In drone mapping workflows, both orthophotos and DEMs often exist in a GeoTIFF file format. The USGS produced DEMs in both GeoTIFF and IMG formats, and is working to produce 3D models through its 3D Elevation Program (3DEP).

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. INFO formatted table files (**.adf** extension) describe the domain extent (boundaries), cell size, type (integer or floating point), compression technique, etc. of the grid. Projection information is stored in a **prj.adf** file within the GRID folder.

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.

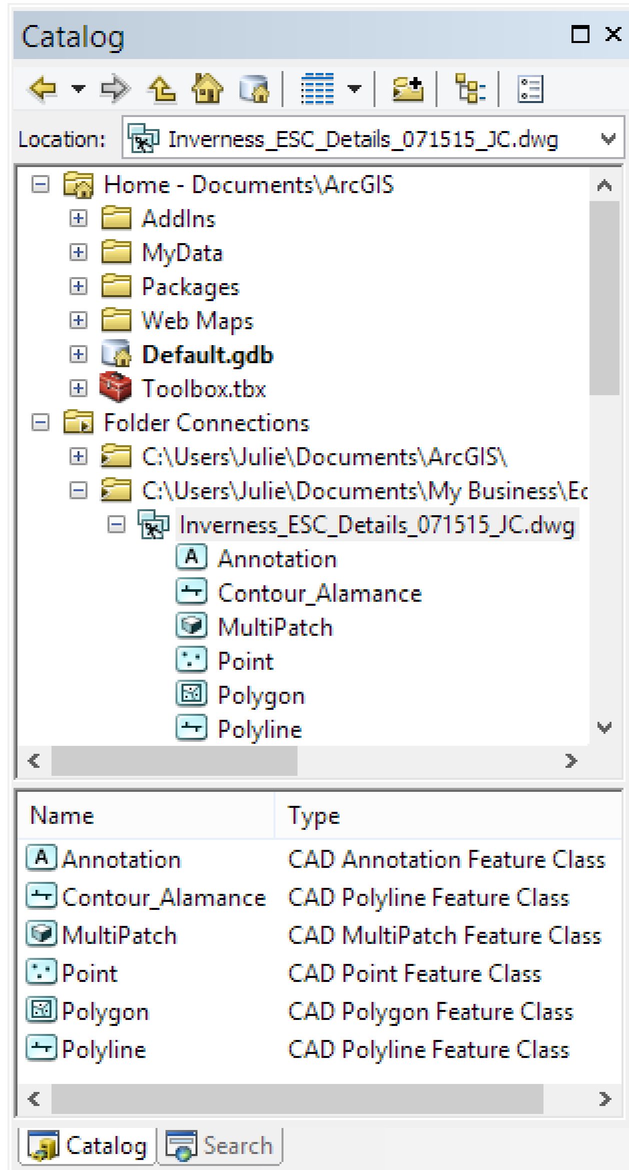
The shapefile format defines the geometry and attributes of geographically referenced features in three or more files with specific file extensions that are stored in the same project directory, or file system workspace. They each possess the same prefix name but must include a **.shp** extension (the 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 in order to speed spatial queries and renderings.

CAD Files

Multiple CAD file formats can be imported into a GIS for editing. 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 (ArcMap) 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.



CAD dataset in (Arc)Catalog

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.

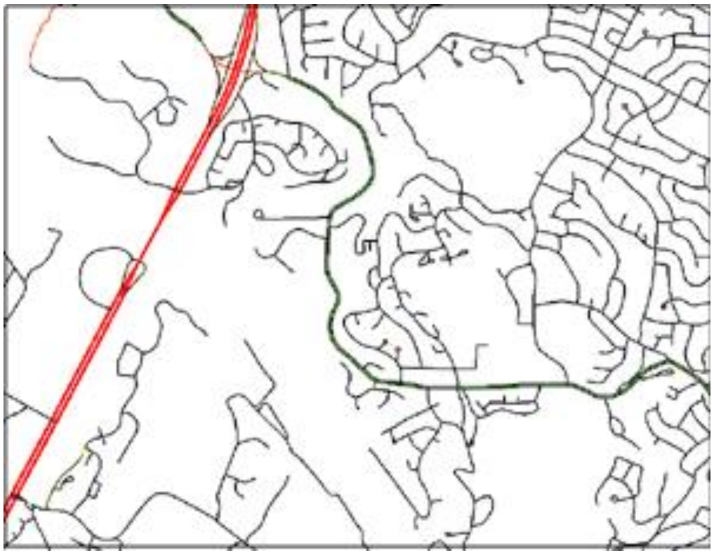
Geodatabases

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). Spatial reference systems consist of a coordinate system plus domain extents. Unlike a shapefile, a geodatabase can hold a collection of related feature classes called a *feature dataset*. In addition to sharing the same spatial reference, feature datasets possess certain user-defined topological, transportation network and terrain dataset, or geometric network relationships. For example, a feature dataset might contain a collection of utility feature classes (gas lines, valves, etc.) for the same project where gas flow is restricted to one direction through certain pipes or where the ability to trace problems upstream or downstream of a point can determine which valve to shut off when a pipe bursts in the geometric network. If you desire to take advantage of advanced editing functionalities with shapefiles, such as topology, you will need to import them into a geodatabase. Different types of geodatabases exist, each distinguished by the number of supporting editors, data storage formats, and size limits. Geodatabase workspace files are recognized by their **.mdb** or **.gdb** extensions, with the *File Geodatabase* (.gdb) being the preferred format due to its larger size limit and ability to accept multiple supporting editors. Projection information is part of the files themselves. Depending upon the type of geodatabase workspace, this information either cannot be viewed directly within your operating system's file manager or shows files which are unintelligible.

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, natural 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. A quick online search can provide some beautifully generated TINs.

Another frequently used vector dataset format includes **Digital Line Graphs (DLGs)**. Similar to Digital Raster Graphics, DLGs are derived from topographic quadrangle maps and distributed by the U. S. Geological Survey. They include lines representing transportation or pipeline networks, streams or outlines of buildings. USGS DLG distribution formats may also use the UTM Projection system. Unlike DRGs, Digital Line Graphs are cartographic map features and thus, are in vector format.



USGS DLG data of roads

Other GIS formats one should recognize include files with the following extensions:

- **.mapx –** ESRI ArcGIS Pro Map File. Used with datasets to conduct GIS analyses and create maps.
  .mxd – older file format (ArcMap document) still used with ArcGIS ArcMap.

- **.lyrx** – ESRI ArcGIS Pro Layer File. A binary file used to store a layer's properties.
  .lyr – older file format still used with ArcGIS ArcMap.

Layer files
Datasets brought into ArcMap or ArcGIS Pro for analyses are often symbolized or classified for optimal visual representation. This symbology or classification is only stored with the map file. That's because datasets, represented as layers in a map, are not actually stored inside the map file, but linked to their storage location. (Datasets can be quite large. Thus, having many datasets as part of your file plus any you have created through geoprocessing would create very large files, indeed.) It is important to distinguish between a layer, as previously discussed, and a *layer file*.

A layer file stores symbology, symbology classifications, display settings, annotation displays and path to the data, among other properties, but not the geographic data itself. In a similar manner, neither ArcMap or ArcGIS Pro maintain a link to layer files. Like the datasets themselves, **.lyrx** or **.lyr** files are separate files on disk. When a layer file is added, the properties of that layer are read into the map, then stored with the map file. Layer files are often saved from datasets using commands within ArcMap or ArcGIS Pro, once these properties are set. This allows one to create or re-create map files with similar mapping schemes.

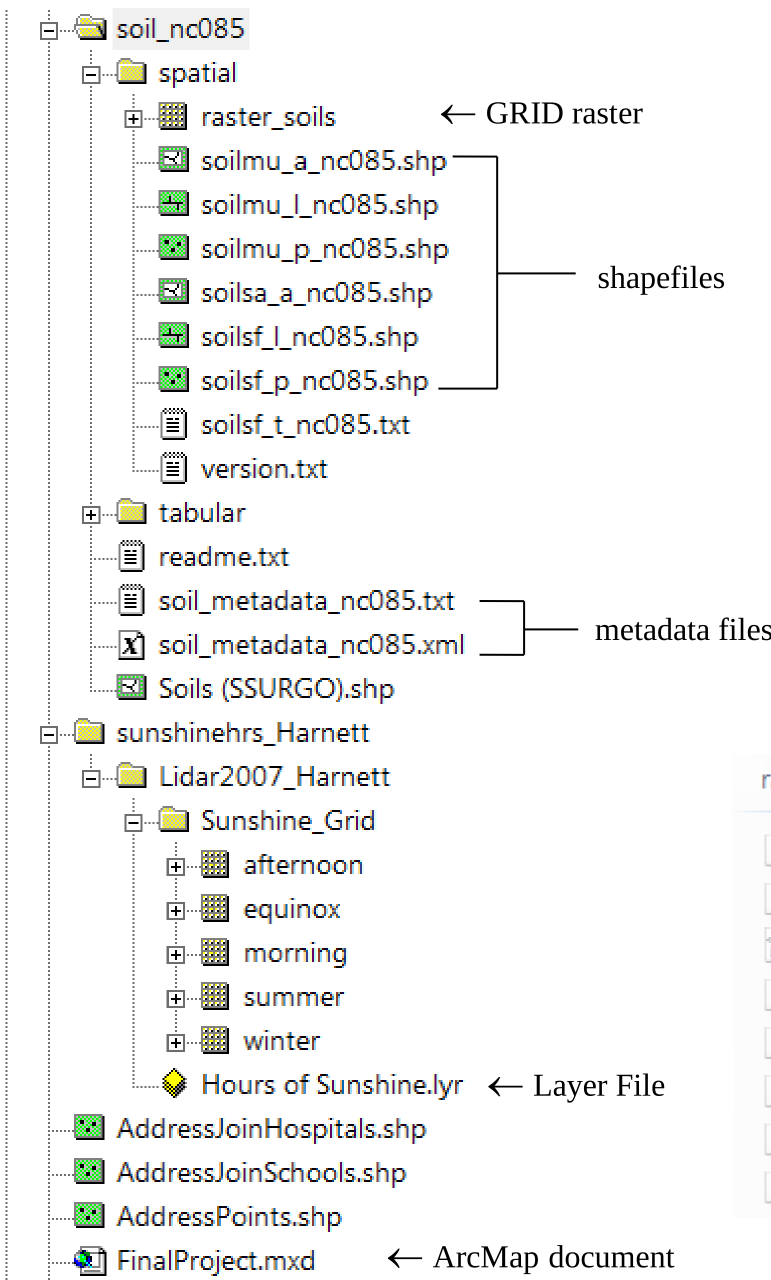
If you are interested in pursuing geographical information science, there are many data repositories available on the web. Several of the government produced datasets are free of charge. Below are some useful places to start searching for available data:

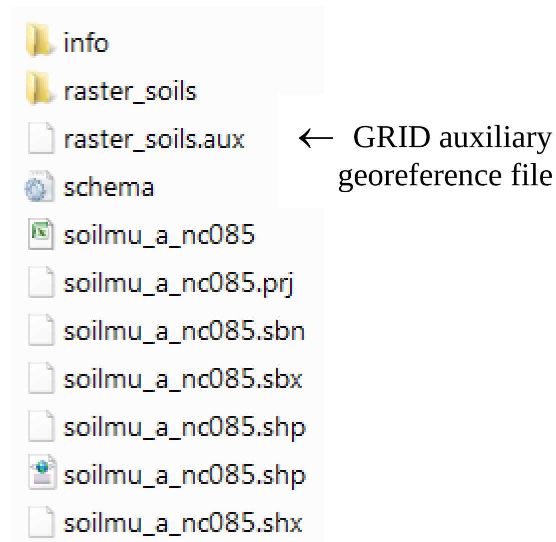
- Data.Gov https://catalog.data.gov/dataset
  This site hosts U. S. federal, state, and local geographic maps and data, applications, and other web sites that have been catalogued for searching in this portal. Registered mapping services allow casual users to build online maps using data from many sources.

- USGS, *The National Map Viewer* https://usgs.gov/tools/national-map-viewer
  This site provides elevation, hydrography, land cover, transportation, and orthoimagery data as a continuous, nationwide set. An entire U. S. dataset can be downloaded, or partial data can be downloaded as determined by a user-defined area of interest. Additional data can be viewed or queried through this viewer.

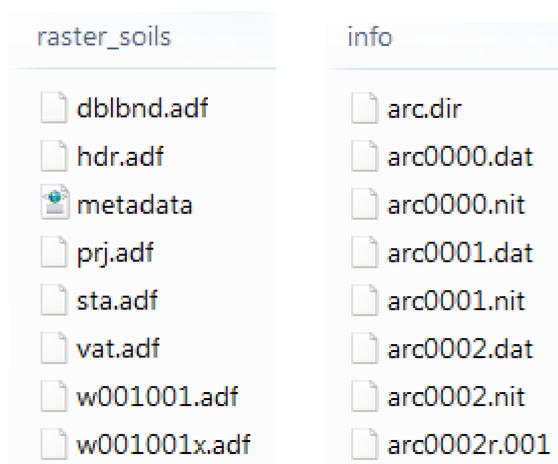
After all of this discussion about file formats, it is important to note that if you are working within ArcGIS Desktop or Pro (and likely others), your file contents will appear differently than they do in Windows Explorer. When managing files with these system architectures, each of the dataset's supporting feature, georeference, topology, and/or index files are displayed as one layer file 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 let's say, 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 (FGDC) 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 were ordered to use this standard to document geospatial data created as of January 1995. Federal policy today provides that non-Federally authored standards endorsed by the FGDC have the same status as FGDC developed standards.

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 and endorsed by the Federal Geographic Data Committee in 2010.

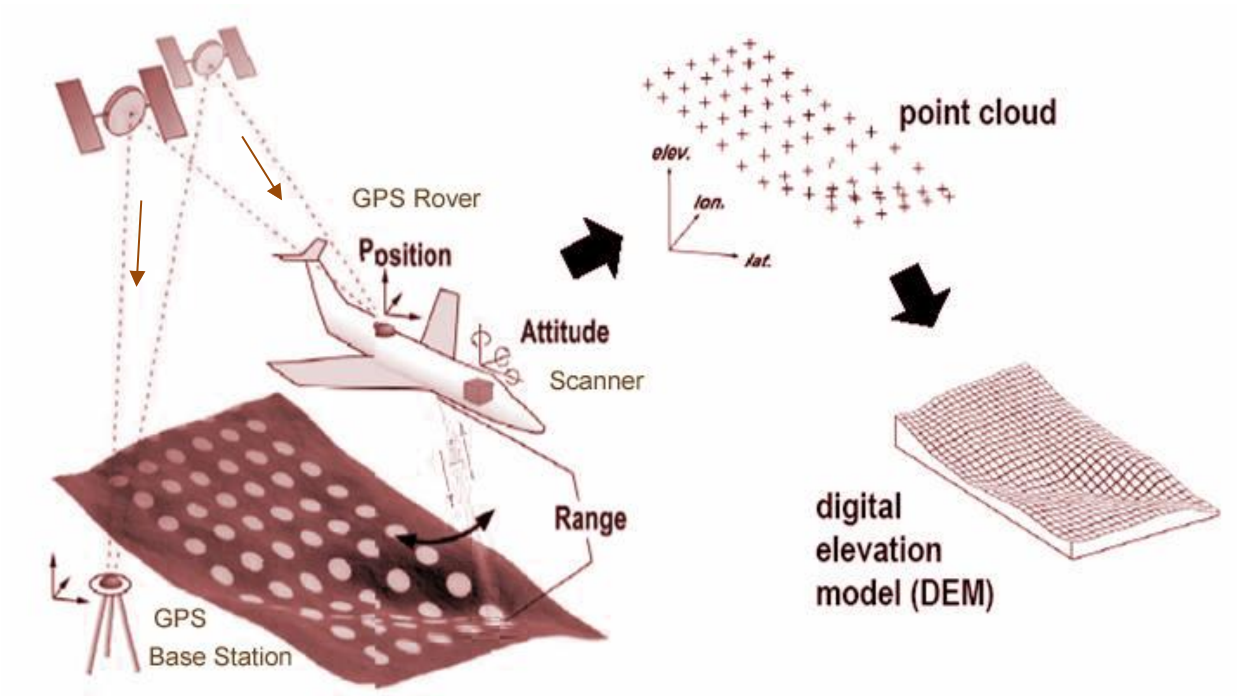
As with coordinate systems, metadata is usually edited according to a predetermined client or government, standards-compliant format.

GIS DATA COLLECTION

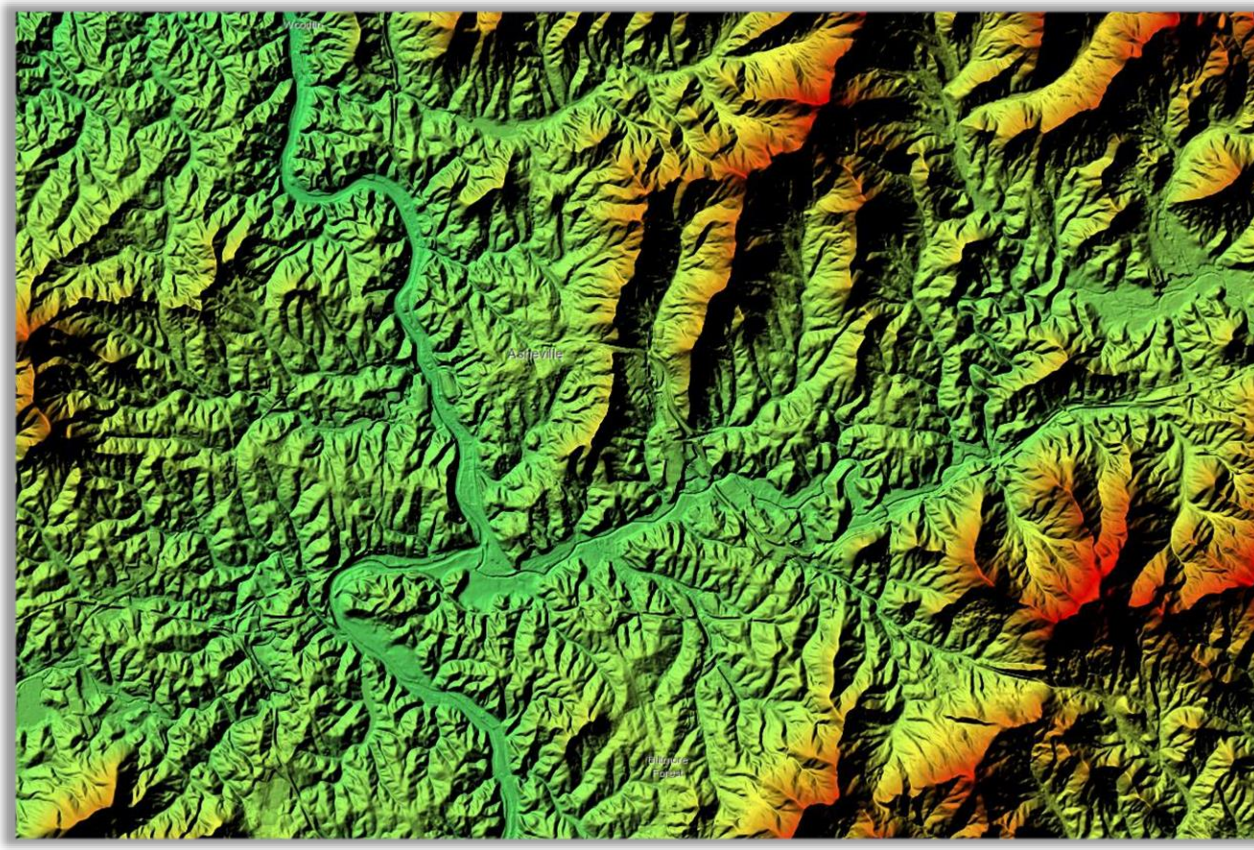
So how is data collected for use in a geographic information system? Digital data can be created by scanning paper maps or aerial photos, imported from spreadsheets or other databases, remotely sensed from satellites or other sensors, and/or captured in the field from traditional electro-optical survey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

Analog data must always be digitized before being added to a geographic database. Scanned paper maps or photographs can be used as raster data, as discussed earlier, or digitized to produce a vector representation. Depending upon the format and characteristics of the data, the analog-to-digital transformation may need reformatting or restructuring. As with any such transformation, the original data may be altered thus, introducing uncertainty. This is where data standards become beneficial.

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 platforms 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 **Li**ght **D**etection and **R**anging, 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 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 the mountains of North Carolina surrounding Asheville (20 ft grid cell)
Source: NC OneMap (2019). North Carolina Department of Information Technology, Government Data Analytics Center, Center for Geographic Information and Analysis.

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* and *y* 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.

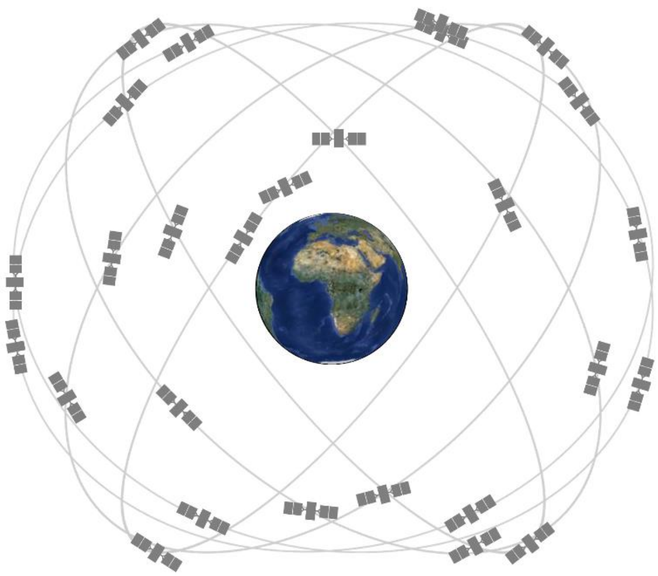
Survey data is increasingly being collected using the United States Global Positioning System. This system can provide three-dimensional positioning data for the same features as those conducted with traditional survey techniques. Surveying with this system can, as with remote-controlled total stations, 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 augmentation systems used to assist the surveyor or mapper, then some of the more popular product vendors.

THE TECHNOLOGY BEHIND THE U. S. GLOBAL POSITIONING SYSTEM

A university faculty member once noted how teaching concepts about the Global Positioning System, or GPS, to students today seemed much easier than a few years ago. That's because 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. It is a system conceived in the 1970's by the U. S. Department of Defense, declared operational in 1995, and currently maintained by the United States government. This system is freely accessible to anyone with a GPS receiver unit.

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) & a modern satellite in orbit (right)
Source: United States Government

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*. These require the use of at least two GPS receivers, one at a precisely known location and relatively close to your roving receiver unit, so that both can pick up the same satellite signals. Since the stationary receiver knows its location, it can use information it receives to correct timing errors coming from the satellite signals. The stationary receiver can, in turn, transmit these corrections to your roving receiver, enabling it to make much more accurate position determinations than without augmentation. 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.

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 some 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 use this system to improve the accuracy of their surveys.

The North American Terrestrial Reference Frame of 2022 that was mentioned earlier will integrate the CORS network into its coordinate reference system.

There are many 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 38 ground reference stations and 3 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 within a few centimeters 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 between 4 – 20 meters approximately twenty years later 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 regards 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 is capable of producing a vertical accuracy of between 1 – 2.5 meters with a 95% certainty. The OPUS claims a general statement of post-processing of coordinate datasets in centimeters, both horizontally and vertically. In general, errors in elevations provided by GPS units are between 1+ and 3 times larger than errors in horizontal positioning.

With that said, there exists a national campaign to produce a new vertical datum based on gravity measurements being taken across the United States and its territories. The goal is to replace the survey leveling-derived heights used by the North American Vertical Datum of 1988 (NAVD88) with satellite-derived heights. This new datum is referred to as the *North American-Pacific Geopotential Datum of 2022*, or NAPGD2022, and is expected to provide vertical accuracies, absent augmentation, to 2 centimeters for much of the country.

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 often engage in a game called "geocaching". It is high-tech, hide-and-seek. Coordinate locations of "treasures" are pre-loaded into GPS units. Since a GPS unit knows its location, it can provide compass directions to the user on how to navigate to these treasures. Mapping grade receivers are for more serious users, and are used for collecting feature coordinates of 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" 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 survey techniques ("RTK surveying") for instance, can provide horizontal accuracies to within a few millimeters, and vertical accuracies to the centimeter level after correction. Real-time kinematic surveying utilizes differential GPS.

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. 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.

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? Often, technicians collect only attributes, such as meter readings on their mapping receiver outfitted with a bar code scanner, while using base map services (e. g., as Google Maps) to reference their location before manually creating a point feature for the GIS database. 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.

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. 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.

DLG – Digital Line Graphs. Digital vector format files that use lines to represent cartographic features such as transportation networks or outlines of buildings. They are a product of the U. S. Geological Survey. DLGs are derived from the traditional USGS topographic quadrangle maps, rectified and georeferenced, and produced at scales of 1:24,000, 1:100,000 and 1:2,000,000.

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.

***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.

GISP – A certified Geographic Information Systems Professional who has met the minimum standards for ethical conduct and professional practice as established by the GIS Certification Institute (GISCI).

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.

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