National Geospatial Technology Extension Network

Maps, Technology and Geospatial Tools

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Why is mapping important?

Maps are graphic representations of geographically distributed features of the physical and cultural environment. They are generalizations which allow users to understand the “where” something of interest is, how it is located with respect to other features, and what shape it takes. Attributes of mapped features provide information about what the objects of interest are. Maps are a means to collect and store geographic information for analysis and decision making. While some environmental problems can be addressed by focusing on small, discrete aspects, these methods often overlook the multi-faceted nature of complex systems. These interrelationships are fundamental to a watershed approach to understanding and managing natural resources. *Watersheds*, by definition, are geospatial, accounting for the land area that drains water above a given point in a stream or common body of water. Maps are essential tools for Earth scientists and natural resource managers. One of the most important initial steps in developing a watershed plan is mapping the boundaries of the watershed and assembling the corresponding base maps of physical and cultural factors that influence watershed function.

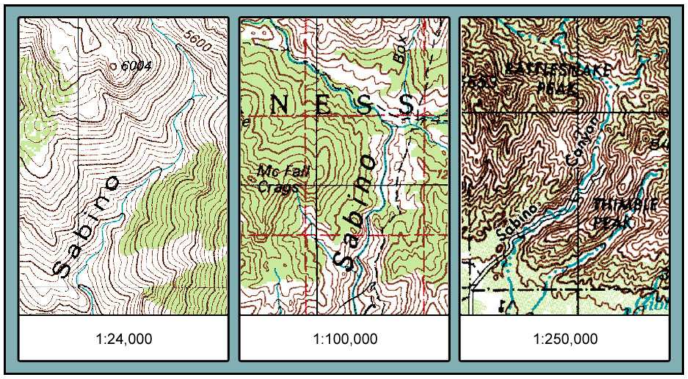
Topography and understanding topographic maps

Among the many mapping tools available, the most commonly used is the topographic map. *Topography* is defined as the relief (relative elevations) of a surface and the relative relations between its natural and man-made features. *Topographic maps* systematically portray the spatial relationship among both the physical features such as contour lines (lines of equal elevation) and hydrographic symbols, and cultural features such as roads or administrative boundaries. Topographic maps are also known as “topo maps.”

Reading a topographic map begins with understanding the extent of reduction necessary to represent a given area of the Earth’s surface. This reduction is known as *scale* and is defined as a representation of the size of something on a drawing, photo or map relative to the size of the real thing. A *map scale* defines the relationship between distance represented on a map and actual distance on the ground, and is often recorded as a representative fraction or ratio, where

map scale = map distance / Earth distance = map distance : Earth distance

For example, 1/1000 or 1:1000 means that 1 unit of measurement (e.g. 1 inch or 1 centimeter) on the map represents 1000 of the same unit of measurement on the Earth's surface. When reading a map scale, the first number (map distance) is always 1. The second number (Earth or ground distance) is different for each scale. One potentially confusing aspect of using fractions or ratios to represent map scale is that the smaller the second number is, the larger the fraction. Thus, the smaller the second number in a map scale, the larger the cartographic scale of the map – meaning a 1:1,000 map (a very large scale map) will provide far more detail, but will cover far less land area than a 1:100,000 map. See Fig. X for illustration.



The U.S. Geological Survey (USGS) has been responsible for creating topographic maps of the United States since its inception in 1879. These maps come in a variety of scales. The most common for natural resource management purposes is the 1:24,000 series (where 1 map inch = 24,000 Earth inches or 2000 feet). Maps at this scale cover an area measuring 7.5 minutes of latitude and 7.5 minutes of longitude and are commonly called 7.5-minute quadrangle maps, also know as “quads” or “quad sheets.” These mapping sheets represent 64 square miles in southern U.S. latitudes and 49 square miles in northern latitudes – thus it takes about 57,000 7.5-minute “quad sheets” to cover the entire U.S. and its territories. These maps are used for local area planning, engineering and recreation purposes. Maps at 1:50,000 to 1:100,000 show less detail, but cover areas large enough for landscape management support. USGS also has smaller scale maps at 1:250,000, 1:500,000, and 1:1,000,000, which cover very large areas on the sheet and are used for regional and statewide planning. The USGS has an excellent webpage with graphic depictions of map scale (http://mac.usgs.gov/mac/isb/pubs/factsheets/fs01502.html).

The content of topographic maps may seem bewildering upon first glance, however there is a method behind all the colored points, lines and areas distinguishing key features. The smaller features of limited extent (such as the location of houses) are often represented by points, whereas much larger features (such as the outline of a large building) may be depicted as areas. In the mapping world, these areas are often known as *polygons*. Colors which catch the eye first when looking at most 7.5 minute quadrangles are green (vegetation), blue (water), gray or red (densely built-up areas) and purple (information updated with aerial photography, but not field verified). Unique combinations of line style and color indicate similar features: brown for *contour lines* (which will be discussed in the next paragraph); blue for lakes, streams, irrigation ditches, etc.; red for land grids and important roads; black for other roads and trails, railroads, boundaries, etc.; and purple for updated features. A series of standardized symbols are used to depict features such as springs, water tanks, wells, mines, buildings, campgrounds, and survey control points.

The brown contour lines on topographic maps show elevation. Each contour line joins points of equal elevation above a specified reference, such as sea level. A contour line represents one and only one elevation and thus never splits or intersects other contour lines (expect in the rare case of an overhanging cliff). Note that the *vertical* distance between contour lines (the *contour interval*) is always equal – the smaller the contour interval, the higher (or more detailed) the vertical *resolution,* or the minimum separation of objects, of the map. The *horizontal* distance between contours, on the other hand, is determined by the steepness of the landscape and can vary greatly depending on the terrain. The closer the lines are together, the steeper the object. USGS cartographers select a contour interval that will best show the shape of the terrain for each individual quad sheet. A flat area in Iowa might need a contour interval of 10 feet to capture some sense of relief. By contrast, a mountainous region of Arizona may have contour intervals of 100 feet or more – any finer would result in contours too tightly packed together to distinguish. Concentric circles of contour lines indicate a hilltop or mountain peak whereas concentric circles of hatched contour lines indicate a closed depression. Contour lines form a V pattern crossing streams with the V pointing upstream. Rounded contour lines generally denote hills or ridges.

Using a topography map to define the boundaries of a watershed

Water flows downhill and thus there is a fundamental relationship between water flow and contour lines. A general rule of thumb is that water flow is perpendicular to the contour lines. For isolated hilltops (concentric circles), water flows in all directions. Ultimately water will flow into progressively larger watercourses and into the ocean (unless it is headed towards a depression with no outlet like Willcox Playa, Arizona). Each tributary leads to a larger stream – and each one of these tributaries has a watershed. Thus, depending on the application or need, large basins may be subdivided into watersheds, which can then be subdivided into sub-watersheds. To help standardize management, the USGS developed a national hierarchical framework of *hydrologic unit codes* (HUC) in 1987. The HUC classification system ranges from regional scale (of which there are 21; an example is the Colorado River) to subwatershed scale (of which there are over 7000 across the U.S.). Since all features within a watershed may influence what drains—or does not drain—out of that watershed, delineating watersheds on maps is of much help to managers, policy makers and the public in understanding how landscapes function. For example, mapping watershed boundaries helps identify where water quality or quantity problems might be by illustrating the water's interaction with other physical and cultural features in the landscape. It also helps define the location of those who impact or are impacted by a well-functioning (or poorly functioning) watershed.

Recall that contour lines form a V pattern when crossing streams with the V pointing upstream. Using this pattern, a watershed may be delineated by using a pencil to follow this pattern upstream to the highest point of the watershed. This is the head of the watershed, beyond which land slopes away into another watershed. The watershed boundary is thus the set of high points from the reach of stream – join these all the way around the stream and the tributaries flowing into it and you have delineated the watershed. Note that high points are generally ridge lines, saddles, or hill tops. For a detailed description of how to delineate a watershed using a topographic map, see the Natural Resource Conservation Service's (NRCS) excellent on-line guide at (http://www.nh.nrcs.usda.gov/technical/Publications/Topowatershed.pdf).

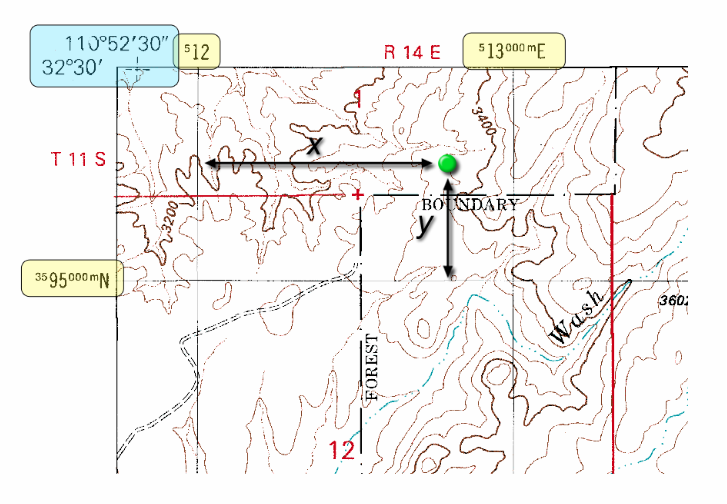
Location reference systems and topographic maps

A *coordinate system* is a recognized reference system for defining points on the Earth's surface and expressing location. Mathematically, a coordinate system is a set of rules for specifying how coordinates are to be assigned to points to represent positions or location. Map coordinate systems can be planer (flat) such as the Cartesian system (x,y) or nonplaner (spherical) such as the *geographic coordinate system* (based on angles) of latitude and longitude. *Latitude* is a north/south angular measurement of position perpendicular to the Earth's polar axis ranging from 0° at the equator to 90° at the poles (the major lines are called *parallels* of latitude). *Longitude* is an east/west angular measurement of position relative to the Prime Meridian (0°), an imaginary circle passing through the poles (the major lines are called *meridians* of longitude, ranging from 0° to plus or minus 180°). To precisely locate points on the Earth's surface, degrees (°) longitude and latitude have been subdivided into minutes (') and seconds ("). There are 60 minutes in each degree (60' = 1°) and 60 seconds in each minute (60" = 1'). Latitude and longitude measurements are indicated by black tick marks in the margins of a topographic map using degrees, minutes, seconds nomenclature, or DDD° MM' SS.S" (e.g. latitude 32° 7' 11.3" N longitude 110° 55' 48.5" W).

Planer coordinate systems are also depicted on topographic maps because they are a means of transforming geographic angles into physical distances. Among the most important elements to understanding and using a planer coordinate system are its a) map projection, b) spheroid of reference, and c) datum. Taken together, these parameters help the cartographer represent the Earth (which is a not-quite-round, 3-dimensional object) onto a flat (2-dimensional) map. *Map projection* is the systematic conversion of locations on the Earth surface from spherical to planer coordinates. (This is not as simple as it sounds – imagine peeling a round orange in a single peel and then trying to lay the skin flat on a table, all in one piece!) Map projection can be visualized by imagining a light source placed at the centre of a transparent globe that is bright enough to project the lines of longitude and latitude (and other map features) onto a nearby sheet of paper. In this analogy, the shape of the piece of paper relative to the globe determines the map projection. Consider how different the projected map would look if the sheet of paper were placed a) tangent to the globe, b) rolled into a cylinder placed around the globe, or c) shaped like a cone placed over the globe. These three are the most common families of map projections, and are termed *azimuthal*, *cylindrical*, and *conic*, respectively. However, they are among the literally hundreds of different individual projections. There is no single "best" projection. Like the orange peel example, the transformation of projecting a spherical surface onto a flat plane will inherently introduce distortion. If a projection is fully *conformal*, angular relationships are preserved; oppositely, an *equal-area* projection preserves areal relationships. Cartographers strive to select the most appropriate projection for the type of map under consideration.

One of the most common coordinate systems in use is the *Universal Transverse Mercator (UTM)* coordinate system. It was developed by the U.S. Army and is used in state and regional maps. It is the basis for all USGS topographic maps. UTM Provides a constant distance relationship anywhere on the map. The UTM system divides the Earth into 60 zones, each covering 6 degrees of longitude. The zones are numbered sequentially starting at the International Date Line and progressing east. Each zone has its own central meridian (a north-south reference line) with coordinates expressed in meters east of the zone origin ("easting") and north of the equator ("northing"). These three figures - the zone number, easting, and northing - make up the complete UTM grid reference for any point and distinguish it from any other point on Earth. Though much less commonly used, UTM zones are also subdivided south to north (designated by the letters C through X) every 8 degrees of latitude. Most of Arizona is in UTM Zone 12, Designation S, though the western edge of the state lies in Zone 11.

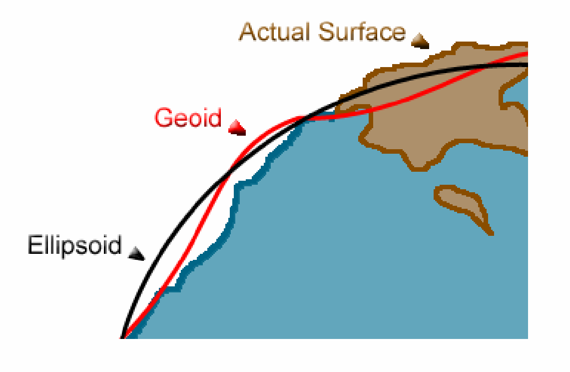
On USGS quadrangle maps, the UTM grid lines are indicated at intervals of 1,000 meters, either by blue ticks in the margins of the map or with full grid lines. Coordinates are written along the sides of the map to designate specific tic marks or grid lines. The two larger numbers are known as principal digits. Tick marks for the principal UTM coordinates are located in the sides of topographic maps. To use the UTM grid, you can draw lines on the map connecting corresponding ticks on opposite edges, or you can place a transparent grid overlay on the map to subdivide the UTM grid. Locations can be identified and distances can be measured in meters (since UTM is measured in meters) at the map scale between any map point and the nearest UTM gridlines to the south and west. The northing of a location is the value of the grid line immediately south of the location plus its distance north of that line. The easting of a location is the value of the grid line immediately west of the location plus its distance east of that line. The northing and easting principal digits give the location to within 1,000 meters (e.g. a coordinate in Tucson, Arizona can be read as UTM Zone 12, easting 506928, northing 3565017). *See example in Fig. X.*



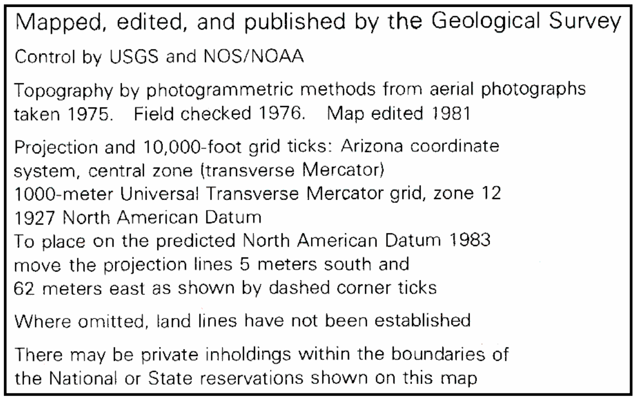
The UTM coordinates in this upper-left corner of a topographic map are highlighted in yellow. The UTM coordinates of the green dot would be easting 512000+x, northing 3595000+y. The numbers highlighted in blue are this map's latitude and longitude at its upper-left corner. Township and range markings are in red.

Another coordinate system is the *State Plane Coordinate System (SPCS)*. It was devised in the 1930s which divides the United States into 125 zones (Arizona has 3 SPC zones), and is very commonly used in local map making, such as in maps of municipalities and counties. SPCS varies considerably from state to state. The Lambert conformal conic map projection is used for states with long east-west dimensions and the transverse Mercator map projection is used for states with long north-south dimensions. These projections are conformal, and essentially project as rectangular grids with little or no distance distortion because the total area involved is small relative to the size of the entire globe. Within any given SPC zone, X-Y coordinates are given in eastings and northings, and are measured in feet. A central meridian passes each zone. In order to ensure that all values are positive, a false origin is created 2 million feet west of the central meridian and some distance south (this distance is different for every zone) below the zone's southern limit. The grid lines for SPCS are sometimes (though not always) included on USGS quadrangle maps.

Map projections are based on a perfect sphere, but in reality the Earth is not truly round. It bulges at the equator, is flattened at the poles and has other depressions and humps. Precise accounting of the true shape of the Earth is called *geodesy*, the science of Earth measurement. The most precise reference comes from measurement of the equipotential gravimetric surface at sea level which results in a geometrically complex shape known as a *geoid*. The Earth's flattened, bulging shape can be described with less complexity with a reference *ellipsoid*, also known as a *spheroid*. This approximated shape of the Earth is used in making maps and is the basis of horizontal control. The placement of a planer coordinate system upon the spheroid is determined by a horizontal reference starting point or *datum*.



There are many reference spheroids (and associated datums) that have been calculated, and each is more accurate in certain parts of the world than in others. Until recently, the USGS and other government agencies used the *Clarke reference spheroid of 1866 (Clarke 1866)* with the *North American Datum of 1927* (NAD27) on topographic maps. NAD27 is an example of a local datum because it was defined by a) the latitude and longitude of an initial point that theoretically intersects the geoid (Meade's Ranch in Kansas), b) the direction of a line between this point and a specified second point, and c) two dimensions that define the spheroid. Maps



Mapped, edited, and published by the Geological Survey

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Topography by photogrammetric methods from aerial photographs taken 1975. Field checked 1976. Map edited 1981

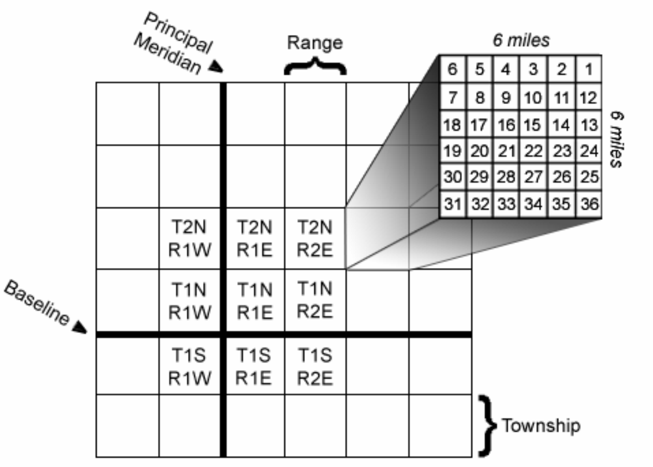
Projection and 10,000-foot grid ticks: Arizona coordinate system, central zone (transverse Mercator)
1000-meter Universal Transverse Mercator grid, zone 12
1927 North American Datum
To place on the predicted North American Datum 1983 move the projection lines 5 meters south and 62 meters east as shown by dashed corner ticks

Where omitted, land lines have not been established

There may be private inholdings within the boundaries of the National or State reservations shown on this map

made more recently employ the *Geodetic Reference System of 1980 (GRS80)* reference spheroid, which is Earth-centered (center of mass), having no initial point or initial direction. The new *North American Datum of 1983 (NAD83)* and the *World Geodetic System of 1984 (WGS84)* are datums based on the GRS80 spheroid. These two datums are very similar and tend to be more accurate than their predecessors. They also allow for cross-regional map standardization. Information about a topographic map's coordinate system, underlying map projection, spheroid of reference and datum are generally documented on the map's lower left-hand corner. *See Fig. X.*

Coordinate systems—which are essential in making a map—are sometimes confused with *cadastre* land information systems, which are public records of the extent, value, ownership and use of land. As provided for in the Land Ordinance of 1785, cadastre in the public-domain states was (and often still is) based on the *Federal Township and Range System* to partition public land for purposes of sale and deeding. In this system, an east-west baseline is intersected at right angles every six miles by meridian lines (running north-south). The area between two meridians is called a *range*. Oppositely, the north-south principal meridian is intersected at right angles every six miles by township lines (running east-west). The area between two township lines is called a *township*, and the six-mile by six-mile squares created by the intersection of range and township areas are also called *townships*. Townships are six miles square, containing thirty-six one-mile square (or 640 acre) chunks called *sections*, which are broken up into half sections (320 acre) and quarter sections (160 acre). A one-sixteenth division is called a quarter of a quarter, for example, NW ¼ of the NW ¼. The descriptions are read from the smallest to the largest. The township and range lines (but not the sections) are often depicted on topographic maps. The system is very commonly used in western states to describe a location of private land in natural resource management. An example of nomenclature for township and range is as follows: T2N, R1E, S 16, NW ¼, NW ¼ refers to the Northwest quarter of the Northwest quarter of Section 16 in Township 2 North (of the baseline), Range 1 East (of the principal meridian). Also, note that every state has a different baseline and principal meridian.



6	5	4	3	2	1
7	8	9	10	11	12
18	17	16	15	14	13
19	20	21	22	23	24
30	29	28	27	26	25
31	32	33	34	35	36

Each township is divided into 36 sections.

Using a compass and a topographic map

A *compass* is a navigational instrument for determining directions. The most common compasses involve a magnetic needle that is free to pivot until it is aligned with the magnetic field of the Earth. The *compass needle* is usually half red and half black or white. The red half always points to the Earth's magnetic north pole. The non-adjustable base of the compass is often called the *compass base plate*. The adjustable part of the compass is called a *compass housing* or a *compass bezel*. It is labeled with the cardinal directions (**N**orth, **E**ast, **S**outh,

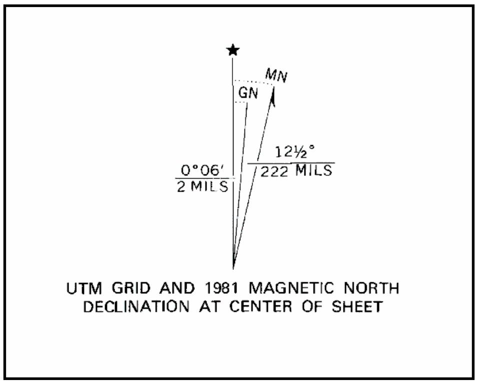
West) and degree markings that are used to find *azimuth* or *bearing*, which is the angular distance measured from the north point at 0° eastward to the direction you are heading; thus, due east would be at a bearing of 90°. There are usually parallel lines called *true north orienting* or *meridian lines* on the compass housing between the **N** and the **S**. To head in a particular direction, turn the compass housing so that the direction and bearing you wish to head lines up with the stationary *direction-of-travel arrow*. Next, with the compass as flat as you can hold it, turn yourself (and the entire compass) until the compass needle is aligned with the orienting meridian lines and the red part of the needle is facing **N**. You can now begin moving in the direction the direction-of-travel arrow is pointing.

Navigation is significantly improved if you combine the compass with a map. First, orient yourself and the map so that the grid lines face north (on all topographic maps and most hiking maps, the north arrow points up, towards the top of the map). This will help you compare features on the map with what you see around you. Next, mark where you are on the map and mark your destination (on topographic maps, it is best to draw a straight line passing through your location and your destination and extending across any one of the map borders). Place the compass on the map so that the edge of the base plate (which is parallel to the direction-of-travel arrow) runs on the line from where you are towards your destination. Also, make sure the direction-of-travel arrow is pointing towards your destination. Next, turn the compass housing (the adjustable part of the compass) so that the orienting meridian lines on the housing are aligned with the meridian lines (the north-south lines) on the map (on USGS topographic maps, it is best of you center the compass housing (N-S) along the meridian lines on the border of the map). If you have this correctly aligned, the **N** on the compass housing will point towards the top of the map (and since you already had the map oriented, it will also be pointing to the magnetic north). The direction-of-travel arrow points along your intended travel vector or direction, which is commonly called a *heading*. Without moving the compass housing, read the azimuth or bearing off the housing where it meets the direction-of-travel arrow. The compass needle should be aligned with the two parallel lines between **N** and **S** on the compass housing, with the red part of the needle facing **N**. With the needle so aligned, aim in the direction the direction-of-travel arrow is pointing and identify a prominent feature (like a tree or a rock outcrop) as far as you can see in that direction and go there. When obstacles deflect you off course, recall the compass bearing of the direction you intend to travel (e.g. 45°), then count your steps (or the time you spend off-course which can be used as a proxy for distance). Once you have bypassed the obstacle, follow the "back bearing" (e.g. 225° is the opposite direction of 45°) for the same steps or time elapsed. Then resume your primary heading.

Before you use the above instructions, it is important that you select a method for dealing with the difference between where the compass needle points, or *magnetic north* (a place that wanders slowly within the Canadian Arctic) and *geographic* or *true north* (the North Pole). This difference is an angle called *magnetic declination*. This accounted for on some maps specifically made for hiking, thus you can proceed as previously described. However, the UTM lines on UGGS topographic maps are not aligned with magnetic north. At the bottom of USGS topographic maps there is a *declination drawing* of the angle of magnetic declination, which will show the difference at the center of the map between compass north (magnetic north or MN) and true north (polar north indicated by the "star" symbol). *See Fig. X.* To complicate things a bit more, the declination diagram also provides the angular difference between true north and the orientation of the map’s UTM grid lines which is termed “grid north,” or GN. This is why most people recommend you take bearings on USGS topographic maps from the border meridian lines, which come closest to matching grid north and true north.

To account for this declination when taking a bearing using the instructions above, it is necessary to subtract the MN declination value if the MN arrow is east or to the right of the true north line, or add the MN value if arrow is to the left, or west, of the line.

Unfortunately, magnetic declination changes over time and location. It varies from 21 degrees west in Maine to 26 degrees east in Alaska, and because the magnetic pole is moving an average of 11.6 km per year in a northwesterly direction, the declination actually changes through time. When accuracy is important, and particularly if the map was created some time ago, it is good to confirm the declination. A useful tool to compute current magnetic declination by zip code is available on-line (http://www.ngdc.noaa.gov/seg/geomag/jsp/Declination.jsp). For example, the declination diagram on a 1983 USGS topographic map in Arizona map suggests a magnetic declination of 13.5 degrees east. In May 2004, the web tool indicated Tucson, Arizona had a magnetic declination of 11.4 degrees east.



UTM GRID AND 1981 MAGNETIC NORTH
DECLINATION AT CENTER OF SHEET

Rather than adding or subtracting each time you take a bearing, you can calibrate most compasses to account for the declination angle by turning a tiny metal screw on the compass housing. For Tucson, Arizona (in May 2004), you would turn the screw to rotate the compass housing so the magnetic north/compass needle mark sits 11.4 degrees to the right (east) of the true north orienting meridian lines.

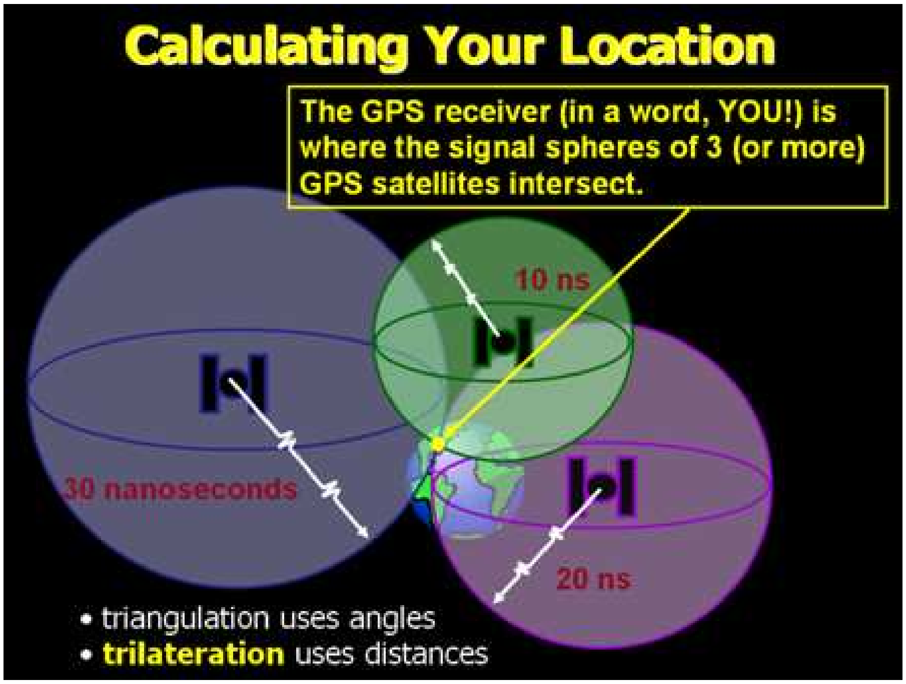
How the Global Positioning System (GPS) works

The *Global Positioning System (GPS*) is a space-based navigational and positioning system. The *space segment* of the system is a network of up to 24 orbiting satellites that continuously transmit radio signals that allow the *user segment* – a *GPS receiver* anywhere on Earth – to calculate its own three-dimensional position, velocity, and time. A GPS satellite is also known as a *space vehicle* (SV). The *control segment* of the system involves a Master Control facility in Colorado that measures signals from the SVs. They are then incorporated into orbital models that compute precise orbital data clock corrections for each satellite. The first and current GPS system made available for civilian use is called NAVigation System with Timing And Ranging (NAVSTAR), and is managed by the U.S. Department of Defense. Its Russian counterpart is the GLObal NAvigation Satellite System (GLONASS).

To compute location, the GPS receiver needs information on a) where the satellites are (satellite location), and b) how far away each satellite is from the receiver (satellite distance). The GPS receiver stores in memory the unique radio signal pattern of each satellite along with *almanac* data describing the orbit of all GPS satellites, satellite clock offsets, and atmospheric delay parameters. Every 30 seconds, each individual satellite also transmits *ephemeris* data (obtained from the Master Control facility), which includes more precise satellite position information and clock settings. Ephemeris data is more accurate than the almanac data. but is applicable over a shorter four to six hour time frame.

GPS is a distance and ranging system based on radio signal travel time, which is converted by the GPS receiver into distance by solving the velocity equation (V = D/T, where V is the speed of light) for distance:

Distance (between GPS satellite and receiver) = radio signal **V**elocity * travel **T**ime



Thus, the GPS receiver measures signal transmission time, which is converted into distance by the above equation. The intersection of the radio signal distances of at least three satellites are used to compute GPS receiver location. This calculation – called *trilateration* – uses the laws of trigonometry, and is conceptually similar to triangulation, but uses distances instead of angles.

The steps in position finding can be summarized as a) GPS receiver obtains the simultaneous signal of three satellites (and a fourth for clock synchronization and altitude calculation), b) the receiver then matches each signal to a unique satellite and its corresponding orbital position, c) using the velocity equation, the receiver computes the distance of each satellite, and d) using trilateration, it computes the position of each satellite relative to the GPS receiver, and finally e) it calculates the receiver's geographic location (e.g. latitude and longitude).

In summary, GPS is a distance/ranging system based on radio signal travel time. To determine location on the ground, the GPS receiver has to know WHERE the satellites are (known location) and HOW FAR AWAY they are (distance). With this information, a trilateration computation, and at least three satellites (and a fourth for validation), your geographic location on the ground can be determined.

GPS sources of error

The accuracy of the GPS measurement varies over time and location. *Noise errors* are associated with the radio signal itself, which results in decreased accuracy of about 1 meter, and within the receiver, which results in decreased accuracy of up to 10 meters. *Bias errors* in the past were predominantly due to *Selective Availability (SA)*, an intentional, random degradation added to the SV signal by the Department of Defense to reduce accuracy by as much as 70 meters. SA is generally no longer employed. Other sources of bias can include errors in ephemeris data (reducing accuracy by 1 to 5 meters), troposphere delays (reducing accuracy by 1 to 30 meters if incorrectly modeled), and unmodeled ionosphere delays (reducing accuracy by up to 30 meters). Also, the internal clock on a GPS receiver is regularly synchronized with the atomic clocks in the SVs and Master Control, but tiny differences represent sources of error of up to 1.5 meters when unsuccessfully corrected by Master Control. *Multipath error* can reduce accuracy by up to 1 meter. It involves situations where SV signals reach the receiver by more than one path, generally through interference caused by nearby structures or other reflective surfaces.

Noise and bias errors are all influenced by satellite geometry relative to the location of the GPS receiver. If the satellites available are clustered together in a small area, the trilateration method used by GPS receivers to calculate a position is less effective. This *GPS ranging error* is measured as *Dilution of Precision (DOP)*. The DOP factor is included in ephemeris data and is computed as a statistical estimation expressing the confidence factor of the position solution based on current satellite geometry. DOP values range from 1 to 6; the lower the value, the greater the confidence in the solution. The DOP factor is multiplied by the summed noise and bias errors, resulting in total GPS accuracy.

In general, these combined errors amount to an accuracy of 20-30 meters on most recreational GPS receivers when SA is off and no additional corrections are provided. User blunders can result in errors of up to hundreds of meters. The most common errors are not properly setting and recording the location format (coordinate system, map projection and map datum).

Methods to improve GPS accuracy

The most basic fundamental way to improve accuracy is to time GPS data collection with more favorable SV conditions in your study area through *mission planning*. Mission planning is possible because periods of GPS signal degradation (including the use of SA), SV status/maintenance, and poor SV configurations for specific times and locations are generally forecast in advance by the Department of Defense. The U.S. Air Force publishes advisories to NAVSTAR users (NANU) (http://www.schriever.af.mil/GPS/Current/current.nnu). Trimble®, a GPS manufacturer, provides a freeware mission planning software called QuickPlan (ftp://ftp.trimble.com/pub/survey/gpsurvey) and downloadable daily almanac files.

GPS accuracy can also be improved through *differential correction*, a process of using the errors measured by a stationary GPS receiver at a known location to improve the measurements of a GPS receiver being used for data collection. The stationary GPS residing at known geographic coordinates is called a *base* or *reference station*. Any positioning errors in the base station GPS positioning measurements are called *pseudorange errors*. A GPS receiver being corrected through the base station is called a *roving unit* or *rover*. The pseudorange errors identified at the base station can be used to correct the positioning data of any rover that has access to data from the same configuration of SVs. Differential correction can take place real-time or during post-processing.

There are a number of different strategies for differential correction, each with associated accuracy improvements and costs. Some inexpensive GPS receivers are capable of receiving real-time *Wide Area Augmentation System (WAAS)* GPS corrections that can reliably improve location accuracy to plus or minus 3 meters. WAAS is being created by the Federal Aviation Administration (FAA) to provide sufficient reliability and accuracy to permit GPS-based instrument approaches in aviation. WAAS is a system of approximately 25 ground-based Wide Area Reference Stations positioned across the U.S. that monitor GPS signals to detect errors. These errors are sent to the WAAS Master Station which generates augmentation messages containing information that allows GPS receivers to remove errors in the GPS signal. The augmentation messages are sent to geostationary communications satellites which broadcast them on a GPS-like signal which can be used by an enabled receiver to supplement the standard GPS calculation of the user’s position. A conceptually similar system called the *Maritime Differential Global Positioning Service* is useful in coastal areas. It is operated by the U.S. Coast Guard Navigation Center (NAVCEN). It consists of two control centers and over 60 remote sites which broadcast correction signals on marine radiobeacon frequencies to improve the accuracy of and integrity to GPS-derived positions to 1 - 3 meter positional accuracy in established coverage areas. Commercial *differential GPS* (DGPS) services such as OmniSTAR® can provide sub-meter accuracy.

A *Local-Area Augmentation System (LAAS)* can also be used for differential correction. This involves finding a local source for the calculation and transmission of correction data. This source might be an airport in the area, or might be as simple as a second GPS unit placed at a known location. A LAAS is typically useful up to 30-50 kilometer radius, depending on terrain and other physical obstructions. Real-time DGPS in a LAAS requires a base station which computes, formats, and transmits corrections through a data link (e.g. VHF radio or cellular telephone) and a rover that can receive and integrate the corrections with each GPS observation. An exceptionally accurate form of real-time DGPS called Real Time Kinematic (RTK) surveying is commonly used when accuracies of 5 cm or greater are required. The RTK rover requires a clear line of sight to 5 satellites to initialize, and generally must be within 20 km of a base station.

Post-processing differential GPS also requires GPS receivers capable of producing DGPS data streams and software to integrate the base and roving unit data. Base station data for post-processing DGPS can be downloaded from the two networks of continuously operating reference stations (CORS) coordinated by the National Geodetic Survey (NGS) (http://www.ngs.noaa.gov/CORS/cors-data.html). It is also possible to create your own base station if you have a second DGPS-capable receiver that can be placed at a *geodetic control marker*. These are permanently affixed points (often a brass, aluminum or concrete marker with a unique NGS identifier) at various locations all over the United States to enable land surveying, civil engineering and mapping to be done efficiently. It is essential that the base station be placed at known coordinates, which make the NGS benchmarks ideal.