Introduction to GPS and its Use in Geology Labs

What is GPS?

The Global Positioning System (GPS) is a system that very accurately tells you your latitude, longitude, altitude, velocity, and time. The United States government has created this system for military applications, but has made it available to anyone in the world. GPS positioning has a wide variety of applications, many unanticipated when the system was first designed. GPS receivers are showing up in commercial and private aircraft, boats, backpacks, cars, and even geology experiments.

How does GPS work?

There are 24 GPS satellites in orbit around the Earth. Each satellite broadcasts a microwave signal that can communicate to a GPS receiver two messages: the precise orbital position of the satellite, and the GPS almanac. Each satellite applies its own individual code to the data it transmits. The receiver can link with a specific satellite by creating the satellite's code and looking to see if any incoming signals are using the same code. After linking, the receiver measures the phase difference between the code it creates and the one it receives from the satellite. This gives the amount of time it took the signal to reach the receiver. By multiplying by the speed of light, the receiver calculates the distance, or pseudorange, to the satellite.

A receiver needs at least four such links to calculate its position. If a receiver knows the pseudorange to and the precise locations of three satellites, it can geometrically find its location. However, because the GPS receiver clock and even the satellite's atomic clock are not perfect, this location will have some error in it. Linking to a fourth satellite corrects for this clock error. The more satellites a receiver can track, the better the accuracy of the positioning. (This, by the ways, is a nice example of a geophysical inverse problem).

DGPS: post processing and real time

Differential GPS (DGPS) is a way of taking out the effects of errors from your positioning data. To do this, you must take positioning data at a location that you know the position called a **base station**, at the same time you are locating the unknown location called a **rover station**. Any time you log GPS data, even if you are standing still, your position will appear to wander. If you take your position at two relatively close locations at the same time, using the same satellites, your position will wander in the same pattern because it is affected by the same errors. Using a computer, you can take out the motion of the unknown location, which will give you a much more accurate answer. Obviously, the accuracy you achieve is only as good as the accuracy to which you know the base location.

DGPS is post processed when raw GPS signals are collected at a rover and corrected later with measurements from a base station. This is usually the most accurate method. Real time DGPS means that the base station calculates and compute a differential correction immediately and communicates it to the rover station, which applies the correction as data are collected.

How well does GPS work?

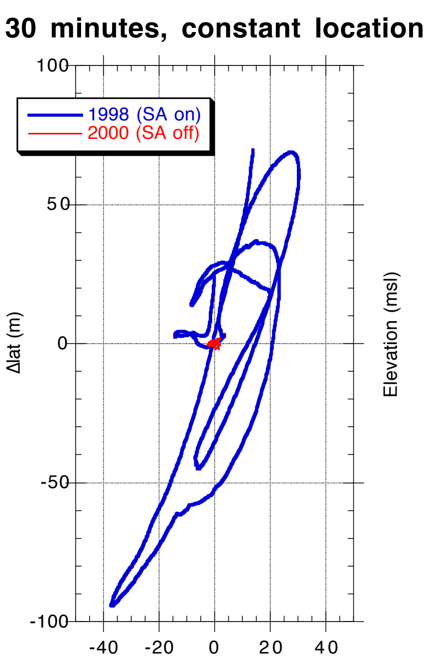
Without differential corrections, a GPS receiver costing as little as $200 can give you your position to within about 10 meters of your actual position on the Earth. Very expensive receivers, used mostly for surveying, can cost as much as $30,000 and provide accuracy to within a few centimeters. You will use the inexpensive receivers (Garmin 12XLs) in this lab.

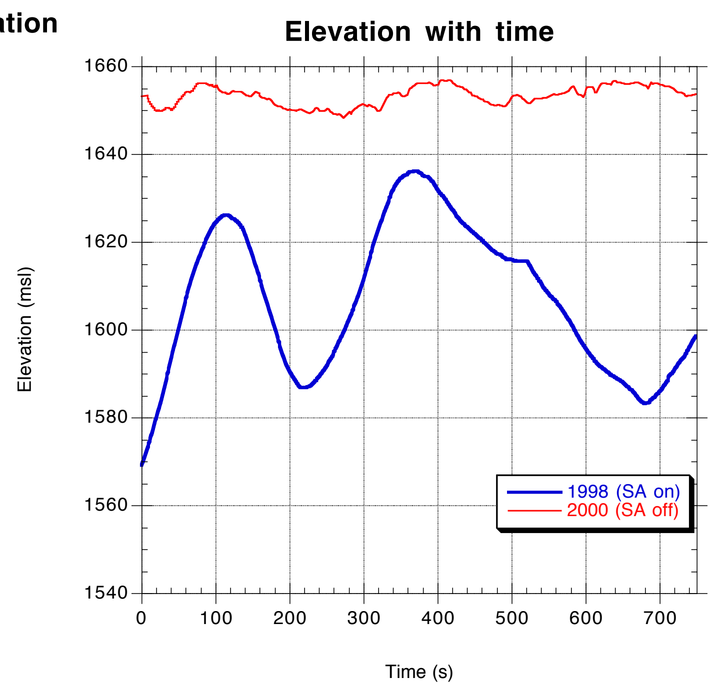
The accuracy and relative ease of use make GPS a replacement for traditional positioning methods in many cases. GPS positioning is often cheaper and faster than other surveying methods, and is often more accurate than maps, and pacing/measuring distances from a known point.

You may be wondering why GPS isn't more precise than it is. There are several factors that contribute to errors in your position. The small factors are delay of the signal caused by the atmosphere, confusion from satellite signals that are reflected off the ground and nearby objects, errors in the orbital positions the satellites claim to be at, and the atomic clocks being off by small amounts. All of these contribute a little to the positioning errors. However, they can also be mostly corrected for with DGPS.

Until 2000, the major error in a GPS position is called selective availability (SA). This is an error that was deliberately imposed by the US government so that enemies cannot use GPS accurately enough to guide missiles and warplanes. SA makes your position appear to wander over time and reduces your uncorrected position to an accuracy of about one hundred meters. This too can be corrected with DGPS.

In mid-2000 the U.S. government turned SA off. Now GPS gives you a position with accuracy of about 10 meters, good enough for many applications. In the figure below, comparing the thicker 1998 lines from a base station at Benson Quad with the thinner line from an inexpensive GPS in 2000 show the large variations introduced by SA in both position and altitude.





- **The GPS Almanac**
  Each GPS satellite continuously broadcasts the GPS almanac. The almanac provides the position in the sky in azimuth and elevation coordinates of all of the satellites at any time. GPS receivers use this almanac to know both which satellites to look for when collecting data and where to look for them. Most receivers will display where the satellites are at the current time. You can use tools such as the online tool at http://www.calsky.com/cs.cgi or that at Garmin (http://www.trimble.com/gnssplanningonline/) to predict how the satellites will appear for a given date, time, and location (for instance, for a lab on 8/31/00 at 2:00 pm we get

Satellite	Elevation	Azimuth
GPS BIIA-22 (PRN 05)	12.6°	56.5°
GPS BIIR- (PRN 11)	39.1°	291.4°
GPS BII-09 (PRN 15)	37.5°	186.7°
GPS BII-08 (PRN 21)	50.7°	108.3°
GPS BIIA-12 (PRN 25)	49.8°	191.0°
GPS BIIA-17 (PRN 29)	55.9°	46.0°
GPS BIIA-27 (PRN 30)	18.5°	90.6°

Users of GPS can use the almanac information to plan the best time to collect data at a certain location. A GPS position is most accurate when the satellites used are spread out in the sky. It is also useful to make sure the satellites you are using will not disappear behind the horizon or behind any local obstructions such as trees and buildings.

- **Making the best possible measurement**

We rarely obtain the almanac information ahead of time any more as the 24 satellites are nearly always running and plenty are visible at all times. The information of where the satellites are in the sky can be quite helpful when in the field. The most common source of large errors in GPS locations at present is multipathing. This is when the radio waves find several paths to the receiver, each a different length. If one is stronger than the direct path to the satellite, the pseudorange is in error and the location will be incorrect. Buildings and large rock walls and the most common reflectors of GPS signals; you can reduce the risk of reflections by blocking the receiver's view of the reflector with yourself, some small rocks, or even a tree. You can sometimes recognize that a satellite's signal is multipathed by watching the signal strength indicator on the GPS: the signal often waxes and wanes cyclically and fairly quickly when multipathing occurs as the direct and reflected signals interfere.

The other great problem in using GPS today is simply seeing the satellites. Metal totally blocks the signal. Although leaves do not effect GPS, branches and tree trunks do. Evergreen forests can be difficult to work in for this reason. Knowing where the satellites are can help in a forest where a clear view of the sky is impossible. You can maneuver to a spot where enough satellites are in view that you can get a location. From there you can measure on the ground to the spot you need located. Also, many receivers will hold a satellite fix once obtained; if you get a location in a clearing, sometimes you can then walk back to a spot where a location was initially impossible and get a valid fix.

Know that your GPS is actively locating itself: many receivers will report the last position with no indication that they no longer receive enough signals to update that location. Usually simply seeing the position change slightly (usually the elevation) indicates that the unit is providing a current location. Often the satellite display screen will show satellites currently being used in some highlight only when a location is current; on the Garmin 12XLs, for instance, the power bar and satellite numbers are in black if being actively used in a location.

- **Converting latitude and longitude differences into distances in meters and feet**

Once you have a position from GPS in latitude, longitude, and altitude, you may want to convert this to other units of measurement. This is useful if you want to know the relative distance between two points in feet or meters. You can use the following conversion to find the distance between two GPS located points. This conversion assumes that the Earth is a sphere but that the distances between points are small enough that the ground can be considered flat.

latitude and longitude [in decimal degrees]
= degrees + (minutes/60) + (seconds/3600)

latitude difference in meters
= latitude difference in decimal degrees x 111,300 m/deg

longitude difference in meters
= longitude difference in decimal degrees x 85,300 m/deg (near 40° N)

total difference between two points
= square root of : (longitude difference^2 + latitude difference^2 + altitude difference^2)

Some GPS software will make this conversion for you. However, it is useful to know how this conversion is made and to have an intuitive feel for what your GPS positions mean.

Frequently it is desirable to use coordinates that are nearly Cartesian in the field. The UTM (Universal Transverse Mercator) projection is frequently used in this case. The projection is a sideways Mercator projection 6° wide along a meridian; positions are expressed as northing and easting and are meters (or kilometers) north of the equator or east of the central meridian (plus 500 km). The declination of northing axis relative to true north is shown on USGS topographic maps, as are the UTM coordinates. Many newer USGS maps show the UTM grid across the map. Nearly all commercial GPS receivers will display UTM coordinates in addition to or instead of latitude and longitude.

- **Datums and accuracy**

It is tempting to read the numbers off a GPS unit and ignore just what in detail they mean. For many applications, this works fine. But this can produce serious errors in some applications. Although things like latitude, longitude, and elevation might seem well defined, in fact they have some slop. Take latitude and longitude first. The Earth, as you should know, is more or less a flattened ellipsoid. For most uses this is all you need and you'd think there would be a single best estimate of this shape, but the Earth isn't exactly a flattened ellipsoid. If you try and estimate the dimensions of the ellipsoid from measurements over only part of the Earth, you find that you get slightly different ellipsoids for different areas. These yield different datums that define latitude and longitude. Nearly all paper USGS topographic maps are mapped to the CONUS 1927 datum for North America (also called the North American Datum of 1927). This was fine until satellite-based descriptions of the shape of the Earth were made and needed; the need for a single global datum led to the WGS 84 datum. GPS units usually use the 1984 World Geodetic System of 1984 (WGS 1984) as their default; this is virtually identical to the North American Datum of 1983 (GRS80 or NAD83). More recent USGS paper maps show the offset between the two datums; in Colorado this amounts to about 40 m. The newest electronic (pdf) topo maps are using the NAD83/WGS84 datum exclusively. On most GPS receivers you can specify in which datum you wish your position reported.

A second error can result from misinterpreting the elevations that are being reported. GPS tends to work in height above a reference ellipsoid; this ellipsoid is a simple geometric figure that only approximates the Earth's surface. The geoid represents where sea level would be in any given spot; it is usually 10s of meters from the ellipsoid (in Colorado, we are about 12 m below the reference ellipsoid). For many applications it can be important to know whether your height is above the reference ellipsoid or above sea level. Because GPS elevations are frequently in error by many tens of meters, this problem is not too significant. DGPS also tends to wipe this away because the reference station is usually tied directly to a specified datum. However, with gravity values varying by 0.2 mGal/m of elevation, merging older and newer data can produce surprises if this issue is not considered.

Most USGS paper topo maps show elevation in the National Geodetic Vertical Datum of 1929 (NGVD29); this was replaced by the North American Vertical Datum of 1988 (NAVD88), which is noticeably higher in mountain areas such as Colorado (http://www.ngs.noaa.gov/TOOLS/Vertcon/vertcon.html can convert between these references; a larger number of tools for converting between different reference frames can be found at < http://www.ngs.noaa.gov/TOOLS/program_descriptions.html>). Nominally, WGS84 should be reporting elevations more or less in NAVD88 heights, but this is not a guarantee as the horizontal and vertical datums are separate. The newest electronic USGS quadrangle maps are using the NAVD88 datum.

Consider, for instance, the survey marker on top of Caribou Hill. The old USGS topo map shows this has having an elevation of 10,502 ft, or 3201.0m, When we surveyed this with GPS gear in 2008, we got an elevation from the ellipsoid of 3190.011 m. However, elevations on topo maps are "elevations above sea level" which far inland means elevation above the geoid, so we add in 12.74m representing the difference between the geoid and the ellipsoid that the GPS reports; this brings our elevation from GPS to 3202.75m. But this is to the 1988 vertical datum, but the topo map was in 1929 vertical datum. We find from the tool above that the difference at Caribou Hill is 1.525m, which we subtract from our GPS elevation to get 3201.25m. As the topo map elevation was only specified to a foot, we have recovered the elevation within the accuracy of the information available.

While we are discussing elevation, it is worth noting how accurate a topographic map is. The USGS adheres to the National Map Accuracy Standards http://nationalmap.gov/standards/nmas647.html, which says that more than 90% of easily recovered points are located within 1/30th of an inch on the map at publication size, and 90% of elevations from contours are within ½ of a contour interval (allowing for slop in the horizontal positions). So on a topo map with 40' contours, if you accurately locate yourself horizontally to within 20m (1/30th of an inch on a 1:24,000 topo map), you should be able to read your elevation to +/- 20'. Of course, actually reading the contours can present an issue, too, so you don't want to get too confident. The latest USGS electronic topo maps seem to be adhering to some different rules listed in the report at < http://pubs.usgs.gov/tm/tm11b2/>; in essence, the USGS has decided to drop many of the accuracy standards from the past in these new maps; accuracy for any given map is now listed in an accompanying XML file. The new maps have dropped the practice of showing the positions and elevations of benchmarks and other surveyed points.

- **GPS in geology labs**

  Geology labs in this class and in other situations require accurate positioning. It is important to know both the location of an experiment and the relative distances between the points where you take data. Knowing the location and boundaries of your experiment allows you or others to repeat the experiment or study other characteristics of the same area of land. During such experiments it can be important to know the distances between certain points on the ground.

  The above discussion should help you anticipate when different location techniques are appropriate. In some cases, a single high-quality location with easier relative measurements to nearby points may be less time intensive than acquiring a larger number of high-quality locations; in other cases, equipment availability might dictate what accuracy is possible and force the use of older methods of determining locations.

Describing your location

As the discussion above should reveal, an absolute location consists of a latitude, longitude, elevation above sea level (or reference ellipsoid), and a reference datum. An alternative is to express the UTM coordinate in terms of the zone (which refers to the central meridian used as the "equator" for that UTM projection), northing, easting, and elevation. (One description of how UTM coordinates are described may be found at http://erg.usgs.gov/isb/pubs/factsheets/fs07701.html). In any geophysical survey one such position is very highly desirable.

Federal Township and Range legal land descriptions are common in the western United States. These descriptions are hardly highly desirable scientifically, but as property lines and many older maps rely on them, they are frequently useful. In addition, unlike latitude, longitude, or UTM points, federal section corners frequently have a marker on the ground (one is near the Caribou cemetery, for instance). The idea is that the land is divided up into 36 square mile townships, each township containing 36 individual sections. (This wonderful geometric ideal is seriously undermined in the west by bad, cutrate surveying and the region's topography:

frequently you will see fractional townships, odd shaped sections, and other blunders). The townships are counted north or south from the Base Line for that particular region and east and west of the Principal Meridian (and yes, Baseline Rd. south of campus is indeed the Base Line for most of Colorado, Kansas, Nebraska and Wyoming: check out http://www.blm.gov/wo/st/en/prog/more/cadastralsurvey/meridians.html). The sections are numbered from 1 in the northeast corner going to number 6 in the northwest corner, number 7 south of 6 going to number 12 south of section 1 and so on to section 36 in the southeast corner (http://www.nationalatlas.gov/articles/boundaries/a_plss.html or http://www.outfitters.com/genealogy/land/twprange.html illustrates the federal land survey system). Within a section descriptions often refer to the quarters of a section and even the quarters of the quarters. Section lines are shown in red on US Geological Survey topographic maps.

As an example, consider the SE 1/4 of the NW 1/4 of section 7, T3N, R5E, Mt. Diablo Meridian. If you read backwards, you find this refers to a township in California in the third township north of that baseline and the fifth east of the Mt. Diablo Meridian. Within that township, section 7 is on the west side a mile south of the NW corner; the northwest quarter being against that western side. The SE 1/4 is the 40 acres in the SE quarter of that quarter section. Although you should avoid these legal descriptions as a primary location in scientific work, many legal and business interests require this information, and many older U.S. publications use these descriptions exclusively.

Relative location and informal locations

Although an absolute location for an experiment is essential, it is also awkward for describing close by locations. For instance, a line of geophones on the ground, spaced 10 meters apart, would be incredibly awkward to describe with a series of latitudes and longitudes that differ only in the thousandths of a degree. The long string of numbers necessary to describe such locations would be difficult to use in the field and prone to typographical blunders in a field notebook. Additionally, the locations themselves tell little of the situation in which data was acquired. Somewhat better are UTM coordinates, which at least are in meters (or km, depending on usage). Legal usages are virtually useless at such fine scales.

Generally we take the approach that we can simultaneously provide locations of equipment and the physical surroundings. The most spartan approach is to define one point as an absolute reference and then measure, by pace and compass, surveying, or some other technique, the other sites of interest from that reference site. A scale map can be prepared from such information. This is the minimal information needed in a tight geophysical survey. It can be helpful as well to describe the physical area around the measuring area—distances to fences can be critical in magnetic surveys, presence of roadbeds can effect several subsurface measurements, individual large trees near a radar profile can be important.

The usual practice is to make a sketch map in the field. While not things of beauty, these should locate the experimental equipment relative to local landmarks and features significant to the techniques being employed. Such maps should have a reasonably accurate scale and an orientation (north arrow). Exact distances should be written explicitly on the map or referred to in a table, as should compass bearings. Enough information must be on the field map that a scale map can be prepared from it and a later worker can find the same spots and repeat the same experiment should the need arise.

You can consider the value of this approach in surveying a cemetery: an excellent absolute location might place you to within 3 meters of your actual spot on the Earth. After completing a survey, you might find that you have located several graves and so you could position them within 3 meters. When directing a gravedigging crew, you can once again only get an absolute location to about 3 meters without special equipment, so you could be as much as 6 meters from the grave identified in the geophysical survey. This could result in embarrassing problems . Similar issues arise in locating buried drums of toxic waste, sewer pipes, mine shafts, etc. These problems are easily avoided by taking advantage of the local landmarks which are easily located relative to the geophysical measurements

Procedure for using Garmin GPS12XL handheld unit

1. Press red button to turn on

2. Satellite status page will appear while GPS unit acquires satellites (will take a few minutes - also don't block the GPS unit's view of the sky)

3. (optional) Mark which satellites are acquired (first time only) - the acquired satellites show up on the histogram at the bottom of the screen

GPS unit #	Satellites

4. Once sufficient satellite signals are acquired, the status page will be replaced by the position page. Note your position in latitude, longitude, and elevation. You can average your latitude and longitude by pushing the “mark” key, then tabbing down to the “Average?” line and then hitting enter. The GPS unit will average until you either hit Page or select “Save?” and Enter. You cannot average your elevation in this way.

5. To turn off, press red button for about 2 seconds (make sure you turn it off when you aren't using it - the batteries wear down fast!)

To alter display, datums, etc.:
Use the page key to go to the "main menu" screen.
Use the down arrow (or right arrow) to select *setup menu*, then press *enter*
Use the down arrow key to select what you wish to alter:
system has controls for contrast and when it beeps, etc.
navigation has
- *format*(arrow down once, enter, then arrow keys to change, enter to exit), which controls how your position is displayed, and
- *datum* (arrow down 2, enter, then arrow keys to change, enter to exit), which controls the geodetic datum (for our usage, WGS 84 is preferred).