Chapter 5: Global Navigation Satellite Systems and Coordinate Surveying

Joaquin Cavieres

Geoinformatics, Bayreuth University

Introduction

Broadly defined, there are two general ways we measure the locations of geographic features.

1. The first uses field measurements, and is described in this chapter. We travel to a feature and physically occupy a location to measure unknown X, Y, and often Z coordinates.
2. The second set of location measurement techniques uses remote data collection, primarily from aerial and satellite images (chapter 6).

For the first point:

Positioning and measurement systems have become quite sophisticated, incorporating satellite and laser technologies, primarily Global Navigation Satellite Systems (GNSS), as well as traditional ground surveying methods.

Figure 1: An artists rendering of a Galileo satellite, part of a planned 30-satellite constellation at the heart of a European Unionled satellite navigation system (courtesy Lockheed Martin).

GNSS basics

Because they are inexpensive, accurate, and easy to use, GNSS have significantly changed surveying, navigation, shipping, and other fields, and are also having a pervasive impact in the geographic information sciences.

GNSS have become the most common method for field data collection in GIS.

There are three more common GNSS systems:

- The NAVSTAR Global Positioning System (GPS) was the first deployed and is the most widely used system.
- There is an operational Russian system named GLONASS that is increasingly used internationally.
- Galileo was developed by a consortium of European governments and industries, with total of 30 satellites in the constellation

There are three main components, or segments, of any GNSS (Fig. 2):

- Satellite segment (Fig. 3).
- Control segment
- User segment (GNSS receivers)

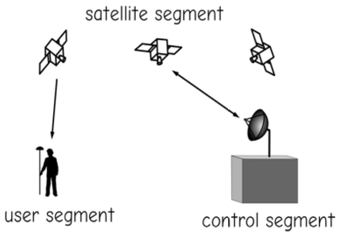

Figure 2: The three segments that comprise a GNSS.

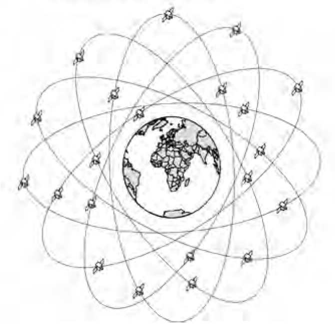

Figure 3: Satellite orbit characteristics

A receiver is an electronic device that records data transmitted by each satellite, and then processes these data to obtain threedimensional coordinates (Fig. 4).

Figure 4: A hand-held GNSS receiver (left) and a GNSS receiver in use (right), (courtesy Topcon, and G. Johnson) (Bolstad (2016)).

The satellite and control segments differ for each GNSS.

- The NAVSTAR GPS includes a constellation of satellites orbiting the Earth at an altitude of approximately 20,000 km.
- GLONASS was designed to include 21 active satellites and three spares. New designs have been phased in as older satellites have expired, and system managers have focused on maximizing coverage over Russia.
- Galileo also implements satellite, control, and user segments. There are 30 satellites planned for the complete Galileo constellation.

GNSS broadcast signals

GNSS positioning is based on radio signals broadcast by each satellite (Fig 5)

Name	Frequency (MHz)
L1, L1C	1575.42
L2, L2CM, L2CL	1227.6
L5	1176.45
P, M	10.23
C/A	1.023

Figure 5: GPS Signals (Bolstad (2016)).

There are two *carrier signals*:

1. L1 at 1575.42 MHz
2. L2 at 1227.6 MHz.

These carrier signals are modulated to produce two *coded signals*:

- The C/A code at 1.023 MHz
- The P code at 10.23 MHz.

The L1 signal carries both the C/A and P codes, while the L2 carries only the P code.

Positions based on carrier signal measurements (L1, L2, and L5 frequencies for the NAVSTAR GPS) are inherently more accurate than those based on the code signal measurements.

The mathematics and physics of carrier measurement are better suited for making positional measurements, $\rightarrow$ however, the measurements require more sophisticated and expensive receivers.

Positions based on carrier signal measurements (L1, L2, and L5 frequencies for the NAVSTAR GPS) are inherently more accurate than those based on the code signal measurements.

The mathematics and physics of carrier measurement are better suited for making positional measurements, $\rightarrow$ however, the measurements require more sophisticated and expensive receivers.

The other GNSS systems operate in a similar manner, with base, or carrier frequencies, and modulated or coded signals embedded within these carriers (Fig. 6)

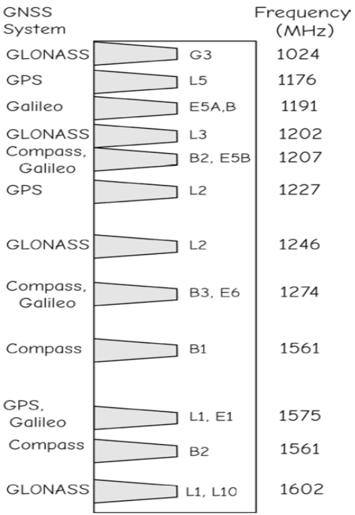

Figure 6: Existing and proposed GNSS broadcast signals, frequencies, and positioning services (Bolstad (2016)).

Substantial effort has been directed at ensuring the NAVSTAR, GLONASS, and Galileo systems do not interfere with each other, and are as compatible as practical.

Range Distances

GNSS positioning is based primarily on range distances determined from the carrier and coded signals. A range distance, or range, is a distance between two objects.

For GNSS, the range is the distance between a satellite in space and a receiver (Fig. 7).

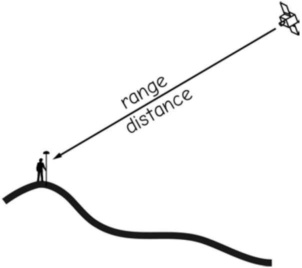

Figure 7: Coverage, relative distance, and detail change from medium-scale (Bolstad (2016)).

The range distance from the receiver to each satellite is calculated based on signal travel time from the satellite to the receiver:

$$\text{Range} = \text{speed of light} * \text{travel time} \tag{1}$$

The difference between transmission and reception times is the travel time, which is then used to calculate a range distance (Fig. 8).

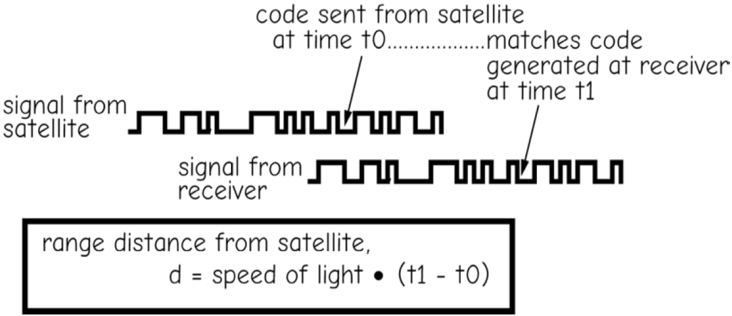

Figure 8: Coverage, relative distance, and detail change from small-scale (Bolstad (2016)).

Simultaneous range measurements from multiple satellites are used to estimate a receivers location. A range measurement is combined with information on satellite location to define a sphere (Fig 9).

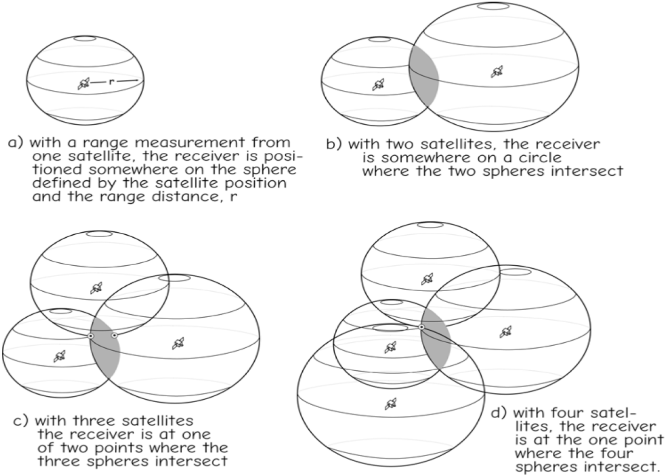

Figure 9: Range measurements from multiple GNSS satellites. Range measurements are combined to narrow down the position of a GNSS receiver. Range measurements from more than four satellites can be used to improve the accuracy of a measured position (adapted from Hurn, 1989). (Bolstad (2016)).

Positional uncertainty

Errors in range measurements and uncertainties in satellite location introduce errors into GNSS-determined positions.

The intersection of the range spheres changes through time, even when the GNSS receiver is in a fixed location. This results in a band of range uncertainty encompassing the GNSS receiver position (Fig. 10)

Positional uncertainty

Errors in range measurements and uncertainties in satellite location introduce errors into GNSS-determined positions.

The intersection of the range spheres changes through time, even when the GNSS receiver is in a fixed location. This results in a band of range uncertainty encompassing the GNSS receiver position (Fig. 10)

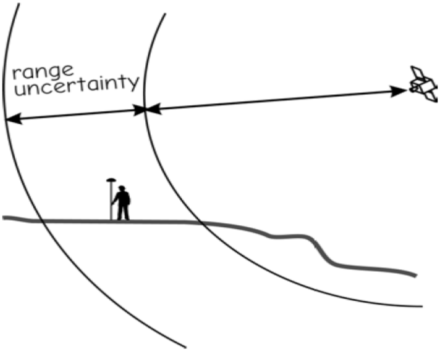

Figure 10: Uncertainty in range measurements leads to positional errors in GNSS measurements (Bolstad (2016)).

Sources of range error

Ionospheric and atmospheric delays are major sources of GNSS positional error. Range calculations incorporate the speed of light. Although we usually assume the speed of light is constant, this is not true.

Range errors occur because the GNSS signal velocity is altered slightly as it passes through the ionosphere and atmosphere; some systems allow satellite screening based on horizon angle, to improve accuracy (Fig. 11).

Sources of range error

Ionospheric and atmospheric delays are major sources of GNSS positional error. Range calculations incorporate the speed of light. Although we usually assume the speed of light is constant, this is not true.

Range errors occur because the GNSS signal velocity is altered slightly as it passes through the ionosphere and atmosphere; some systems allow satellite screening based on horizon angle, to improve accuracy (Fig. 11).

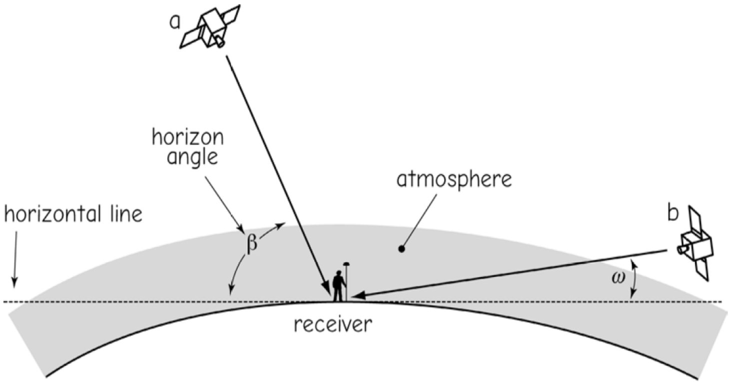

Figure 11: GNSS receivers often discard signals from satellites near the horizon. As this image shows, signals from satellites high above the horizon (a) with high horizon angles (β) have shorter path lengths in the atmosphere than low-angle satellites (b, with angle ω). Atmospheric delays and hence range errors are larger for satellites with low horizon angles. Typically a mask is set at approximately 15 degrees above the horizon, and satellites are ignored if they are below this limit. (Bolstad (2016)).

These physical models reduce the range error somewhat. Alternatively, correction could be based on the observation that the change in the speed of light depends on the frequency of the light.

Receivers also introduce errors into GNSS positions. Signals may reflect off of objects prior to reaching the antenna. These reflected, multipath signals travel a farther distance than direct GNSS signals and so introduce an offset into GNSS positions.

Satellite geometry and dilution of precision

The geometry of the GNSS satellite constellation is another factor that affects positional error. Range errors create an area of uncertainty perpendicular to the transmission direction of the GNSS signal.

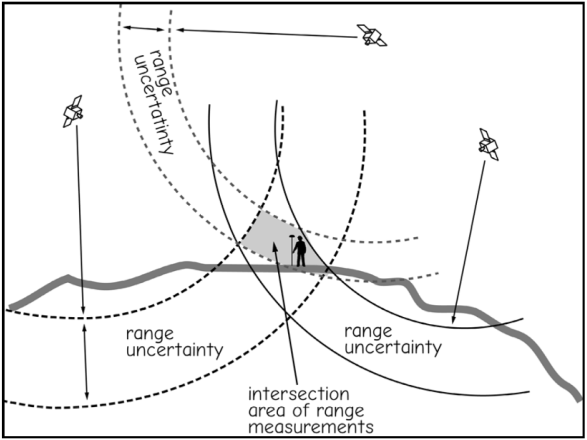

Figure 12: Relative GPS satellite position affects positional accuracy. Range uncertainties are associated with each range measurement. These combine to form an area of uncertainty at the intersection of the range measurements. (Bolstad (2016)).

These areas of uncertainty from different satellites intersect, and the smaller the intersection area, the more accurate the position fixes are likely to be (Fig. 13)

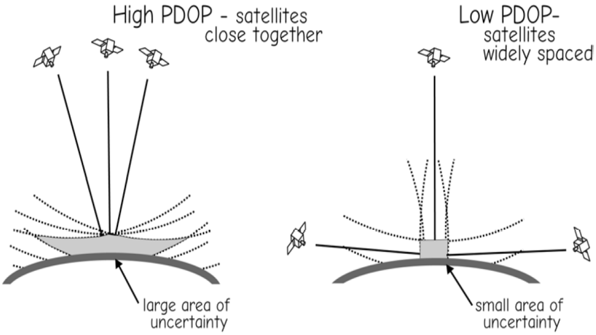

Figure 13: GPS satellite distribution affects positional accuracy. Closely spaced satellites result in larger positional errors than widely spaced satellites. Satellite geometry is summarized by PDOP with lower PDOPs indicating better satellite geometries (Bolstad (2016)).

Range errors and DOPs combine to affect GNSS position accuracies. There are many sources of range error, and these combine to form an overall range uncertainty for the measurement from each visible GNSS satellite.

GNSS accuracies depend on the type of receiver, atmospheric and ionospheric conditions, the number of range measurements, the satellite constellation, and the algorithms used for position determination (Fig. 14)

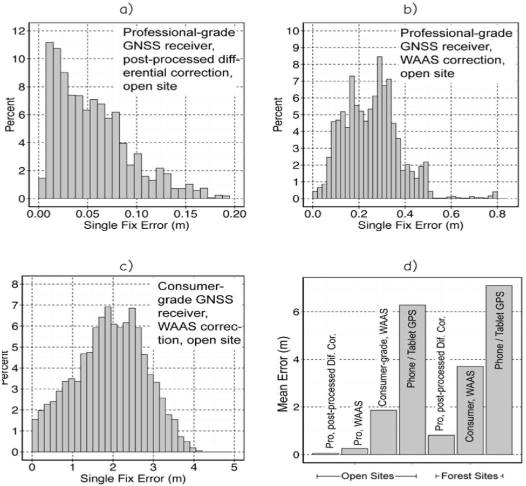

Figure 14: Observed GPS error distributions for various receivers under open sky conditions (a through c) and mean error under open sky and dense deciduous forest canopy (d) Bolstad (2016)).

Differential correction

The previous sections have focused on GNSS position measurements collected with a single receiver. This operating mode is known as autonomous GNSS positioning.

An alternative method, known as differential positioning, employs two or more receivers.

Differential positioning measurements are used primarily to remove most of the range errors and thus greatly improve the accuracy of GNSS positional measurements. The positioning entails establishing a *base station* receiver at a known coordinate point (Fig. 15)

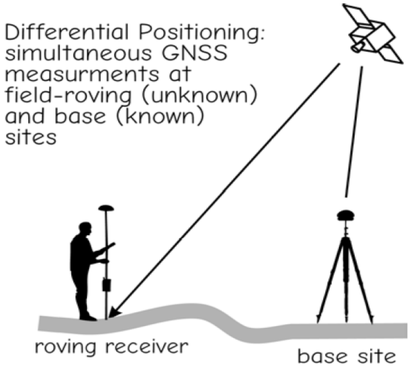

Figure 15: Differential GNSS positioning (Bolstad et al., 1990)

In differential correction we use the known base station position to estimate the timing errors and hence range errors.

If we are very careful about surveying the location of our base station, then the errors in the base-to-satellite measurement are almost always smaller than the range errors contained in our uncorrected timing measurement.

Real time differential positioning

An alternative GNSS correction method, known as real time differential correction, can be appropriate when precise navigation is required.

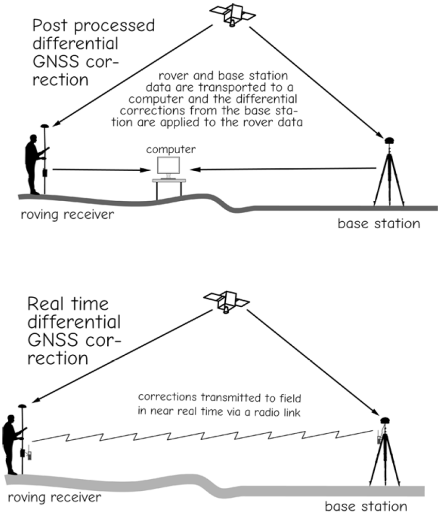

Figure 16: Post-processed and real time differential GNSS correction (Bolstad et al., 1990).

The accuracy of real time differential correction is substantially better than autonomous GNSS, and accurate locations are determined while still in the field.

WAAS, augmentation, and satellite-based corrections

There are alternatives to ground-based differential correction for improving the accuracy of GNSS observations. One alternative, known as the Wide Area Augmentation System (WAAS).

Thank You

References I

Bolstad, P. (2016). *GIS fundamentals: A first text on geographic information systems*. Eider (PressMinnesota).