High-Precision Positioning Unit 2.2 Student Exercise: Calculating Topographic Change

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Change is an inevitable part of our natural world and varies as a function of space and time. Geomorphic change is a diverse process manifesting as both diffuse and concentrated actions varying from channel migration to incision or hillslope creep to mass movement. Additionally, we can quantify many other objects including boulder or log migration down hillslopes or riverbeds. To assess and make informed decisions about the impact and variation of change within our environment, we must develop skills to categorize and quantify these processes. GPS/GNSS surveys that have the advantage of temporal and spatial data distribution allow us to quantify these changes with relative ease. Continuous monitoring or reoccupation of a site over time series allows us to analyze changes in position, which indicate direction and speed of landscape elements.

Introduction

In this unit, you will apply knowledge learned from working with GNSS surveys and point data to analyze and quantify changes in point data. Additionally, you will be challenged to think about how GNSS errors arise and how they might propagate through change detection equations.

Change detection is the act of identifying and quantifying how an object has moved from one location to another. GNSS systems are excellent tools for detecting change due to their ability to produce time series data of an object's motion and to compare them in a georeferenced coordinate system.

Quantifying Change:

GNSS data describes the three-dimensional positioning of an object to some reference frame. Cartesian coordinate systems (*X,Y,Z*) and geographic coordinate systems (Latitude, Longitude, and Height) are two contrasting ways to approach establishing a reference frame and displaying data. The system that is used as a reference can have a great impact on the way data is visualized. However, both systems can be georeferenced for precision positioning, and they can be projected back and forth with relative ease.

Cartesian

GPS/GNSS point data is three-dimensional and can be described simply in a Cartesian system of *X,Y,Z* measurement. These measures are referenced around some origin, which can either be local or georeferenced. Local origins are arbitrary starting points that describe movements relative to each other and the origin with arbitrarily selected orientations for *X,Y,Z*. Usually *Z* is vertical distance, with *X* and *Y* describing perpendicular directions on a horizontal plane, often with one oriented north–south and the other east–west. Georeferenced origins are often geocentric, with the fixed origin of the *X,Y,Z* system at the approximated center of the Earth. However, geocentric coordinates and Cartesian systems can complicate the interpretation of positions, because the axis orientation is not relative to the ground's surface.

By using a Cartesian system with a local origin, one that can arbitrarily be assigned, we can quickly compute the difference between any two points without need for complicated geometries such as ellipsoidal transformations in a geographic system. The distance between any two points on one axis of a three-dimensional position can be expressed as the difference between its initial and final position, example *dX*.

$$dX = Xfinal - Xinitial$$

Any two dimensions in a Cartesian system can be differenced using Pythagoreans theorem.

$$dXY = \sqrt{dX^2 + dY^2}$$

Similarly, we can calculate a three-dimensional displacement in *X,Y,Z.* This is sometimes called slope distance, *ds*, and is the total distance from point A to B, where A and B describe the initial and final position of some object.

$$ds = \sqrt{dX^2 + dY^2 + dZ^2}$$

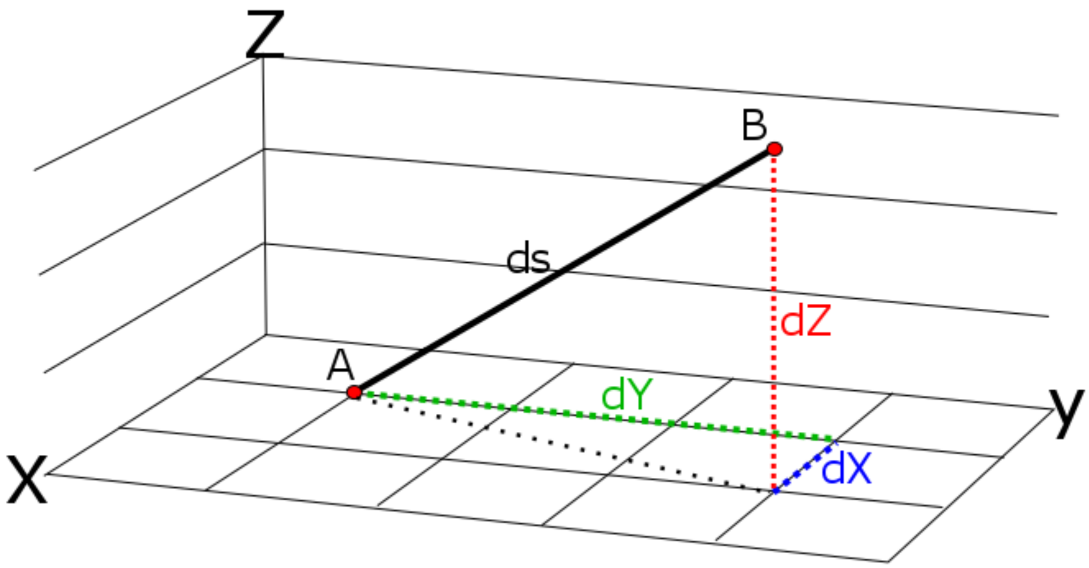

Figure 1: An illustration of the geometry of three-dimensional distances between two points. In change detection, A and B would represent the same object with its locations taken at two different times, i.e. Time A and Time B. *dX, dY, and dZ* represent the change in distance for a single axis. The slope distance, *ds*, is the total distance, or change in position, between A and B.

A Cartesian coordinate plane has a local origin of (0,0,0). An object has moved from its original position at the origin, A (1,1,0) to a new position, B (2,4,3).

1. Calculate the total distance, *ds,* the object has moved.
2. How would the way location or orientation of the origin (0,0,0) affect the way you interpret results. (ie., as negative numbers). Which way is up?
3. What is the advantage of setting a local reference point—e.g. a base station set to (0,0,0)?

Geographic

Geographic reference frames describe positions relative to the earth's surface often in latitude, longitude, and height. Latitude and longitude measure degrees of offset along the earth's surface oriented based on cardinal directions, north, south, east, and west. Because the Earth is neither perfectly circular nor elliptical, a significant amount of work is dedicated to producing the best fit model of the Earth's shape. The fundamentals of geodesy, which allow for these models and transformation between Cartesian and geographic systems, are beyond the scope of this assignment. In general these transformations can be done quickly in software such as ArcMap.

Look at Figure 2, then discuss as a small group and individually answer the following:

4. How does projecting a planar measurement (e.g. line) onto a curved surface affect its distance?
5. How does height or elevation change with the reference point you choose?

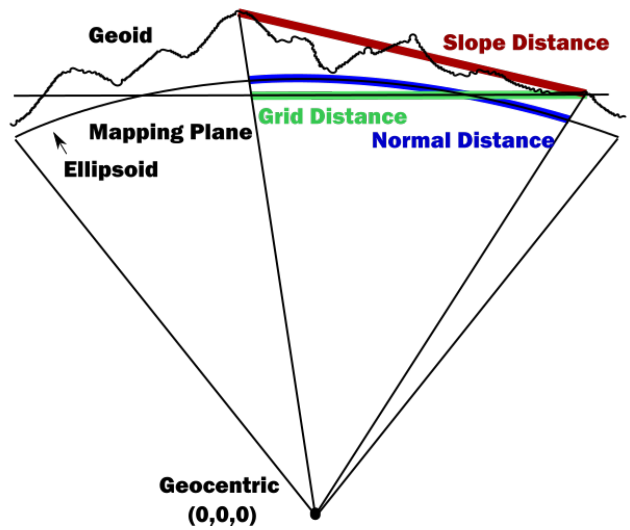

Figure 2: An angular slice of the globe, illustrating the measurement of various geodetic distances using grid, normal, and slope lengths. Note how the length of these lines would change with varying topography and with differences in how mapping planes are selected. Slope distance is measured from the topographic surface. Grid distance is measured along the "flat" mapping plane or projection. Normal Distance is measured along the Ellipsoid. The three distances shown all have the same angular separation.

Surface Change and Visualization

A common way to analyze geomorphic change is through differencing data sets, employing similar equations as described previously. Often GNSS data is used to create or reference digital elevation map (DEM) data derived from other sources as is described in Unit 2.1 Measuring Topography. Digital elevation maps contain data about surface elevations, which are interpolated from multiple point measurements such as GNSS or LiDAR. A DEM only describes a surface at a singular time. Landscape evolution often occurs at a rapid pace, and it is possible to record changes through time with multiple GNSS surveys. By differencing the time series from each other, you can extract the distance and direction of change over time.

One way of visualizing GNSS and DEM changes is in map view through vectors and color gradients. GNSS velocities from a survey are shown as arrow vectors, with the length of the arrow symbolizing the magnitude of the velocity and the direction indicating the net direction of motion. The DEM underneath shows only movement in the *Z*-axis, changes in elevation. Changes in elevation on the DEM are shown using a bicolor color ramp.

Precision of Movements and Error

As discussed in Unit 1, GNSS positioning is the result of trilateration of the antenna by 3 or more satellites. The most favorable configuration is a wide spread of satellites across the available sky. This creates the greatest difference between individual signals and refines precision. However, even the greatest distribution of satellites across the horizon produces twice as much error in the vertical direction than the horizontal. This is because, unlike horizontal distances, vertical distances are poorly constrained due to geometry. You can think of it as physical lines connected to an object. If three people held cords attached to an object and they spread themselves evenly around said object, they could very well constrain its ability to move side to side.

Elevation Change from 2002-10 DEM Difference Mapping
Salmon Falls Landslide, ID

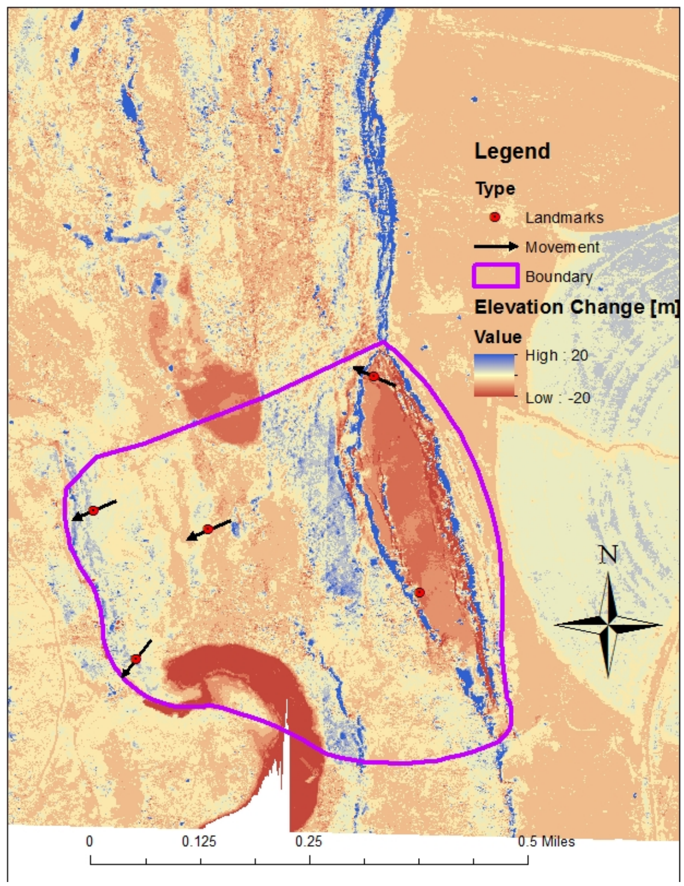

Figure 3: An elevation change map from the Salmon Falls landslide. The map was produced using two DEM maps derived from terrestrial LiDAR surveys. Additionally, GNSS surveys of 5 landmarks established on various features of the slide give a sense of velocity and direction for slide. Elevation change detected from the DEM is symbolized using a bicolor color ramp with red showing subsidence and blue uplift in cm. Notice the potential co-registration issue along the canyon rim. The canyon rim should be stationary, but seems to show uniform uplift along the whole rim. This is potentially a misalignment of images, a problem that can be corrected with proper GNSS survey of ground control points on the canyon rim.

See Figure 3.1 A cross-section illustration of the landslide slump.

Change in Surface Elevation

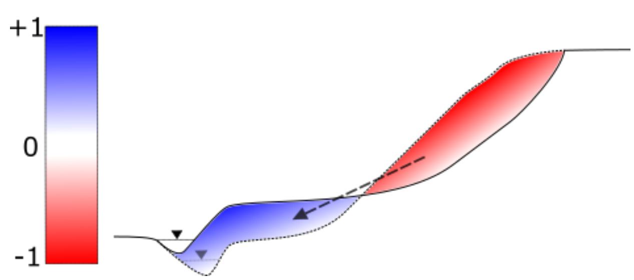

Figure 3.1: A cartoon transect of an earth movement indicating surface color as they would be visualized on a DEM map. Red indicates the removal of the upper slump block resulting in decreased elevation. Blue indicates areas where the slump deposited and therefore surface elevation increased.

Many sources of error contribute to the final position. However, the object would still be able to bounce up and down with significant freedom. Likewise, the vertical position of a GPS signal can only be constrained from above and not below, which significantly reduces its precision.

Many sources of error contribute to the accuracy of the final position including clock timing, satellite position (ephemeris), multi-pathing, and atmospheric attenuation. These errors are summed in the product of dilution of precision (PDOP) and precision estimates provided by the receiver for any single data point. However, with change detection you are differencing two data points from each other and must therefore consider the error that is contributed by both. If the difference between two points is greater than the sum of their errors (1), then we can consider the change to be detectable. In the other case, if the total error is greater than the difference between the two points (2), then change is not detectable. Note that in (2) the error bars for A and B overlap, indicating their error is too great to detect change.

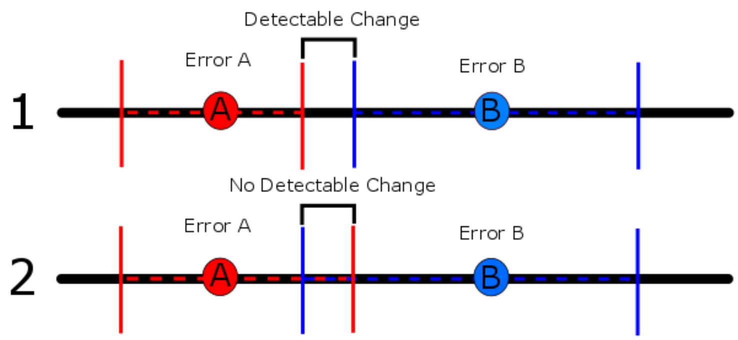

Figure 4: Examples of detectable and no detectable change.

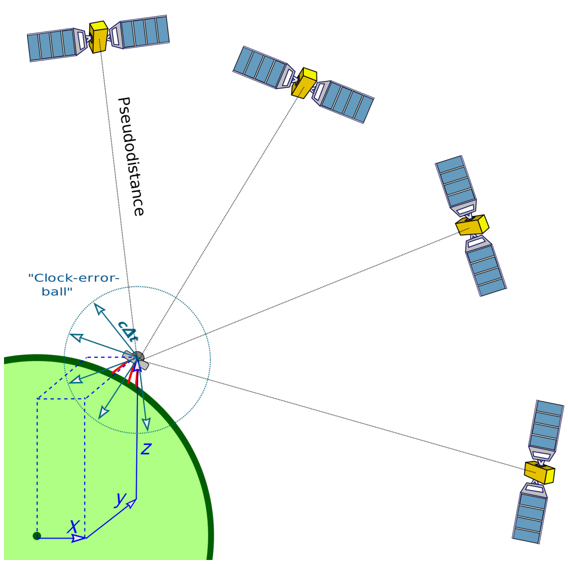

Figure 5: A cartoon representation of satellite network geometry, Cartesian coordinates, GNSS positioning, and error. Clock, atmospheric, and multi-path error is significantly reduced by processing baseline between two stations. This is resolved by processing a base station through OPUS or another online solution and then correcting baselines with the rover or second station such as in the Kinematic GPS/GNSS Survey Methods manual, Section 5.3.

Questions

Think back to the Accuracy and Precision assignment and the Introductory lectures, and answer the following questions about how accuracy and precision relate to making measurements for change detection.

6. How does accuracy and precision relate to error?
7. How does accuracy and precision relate to our ability to measure change? Error?
8. How could you design a research problem so that the measurements you take are sufficient for the change you are trying to detect?
9. Think of one research problem that could be solved for a kinematic GNSS survey. Justify why the kinematic survey is the right technique for the given application and explicitly state the estimated amount of change you want to detect, the accuracy you need in order to detect this change, and the potential error that you can accommodate in your survey and still be able to detect change.

Rubric

Component	Exemplary	Basic	Nonperformance
General Considerations	Exemplary work will not just answer all components of the given question but also answer correctly, completely, and thoughtfully. Attention to detail, as well as answers that are logical and make sense, is an important piece of this.	Basic work may answer all components of the given question, but some answers are incorrect, ill-considered, or difficult to interpret given the context of the question. Basic work may also be missing components of a given question.	Nonperformance occurs when students are missing large portions of the assignment, or when the answers simply do not make sense and are incorrect.
Part 1: Questions 1–8	9–10 points: Answered all questions correctly. Students should illustrate: They know how local vs fixed-reference frames affect how you interpret positional measurement Depending on reference frames, distances measured can be significantly different on large scales (over 10+ km) Accuracy, Precision, and Error must all be accounted for in measurements. Errors from multiple sources add up and must be accounted for, along with estimated accuracy of the tools used. Error must be less than the amount of change detected in order for change to be considered significant.	5–8 points: Answered all the questions, missing 1–2 critical points	0–4 points: Missed more than 2 of the questions or did not complete them.
Question 9:	5 points: Student provides the amount of change they need to detect and makes a reasonable estimate of the accuracy and error measurement. The accuracy doesn't exceed the capability of RTK, which is 2–3cm.	3–4 point: Student demonstrates they understand the system and comes up with a survey that could be accomplished with GPS, but may make some unreasonable assumption in accuracy or error.	1–2 points: The student makes unreasonable assumptions on the accuracy of equipment or completely fails to justify how an RTK survey could solve the problem.