In the mapping professions, handling spatial data can be challenging (e.g., data alignment). Often, a better understanding of horizontal and vertical datums can reduce the difficulties. Penn State’s World Campus offers “Map Projections for GIS Professionals” a course on understanding the role that datums, map projections, and grid systems play in spatial data.

This course is designed for professionals who work with spatial data but are not confident in their understanding of these topics. This ten-week course presents individual concept galleries that provide background on each topic. As a way to test understanding, each week participants are given practical assignments that link the concepts to handling spatial data. For more information check out worldcampus.psu.edu/degrees-and-certificates/geographic-information-systems-gis-masters/overview

A Coordinate Location
By its very nature, geospatial data is tied to the Earth’s surface. However, defining the exact location on the Earth’s surface is not necessarily straightforward. Consider this simple question: where is 40° 47’ 36” & 77° 51’ 36” exactly located? These coordinates could pinpoint several places. Unfortunately, uncertainty is high because the following details are not provided:

1. Which value is latitude & which value is longitude;
2. What direction is attached to the coordinates (e.g. N/S, W/E);
3. Are these geodetic or spherical coordinates;
4. If the coordinates are geodetic, what is the associated datum?

For now, assume 40° 47’ 36” is latitude and 77° 51’ 36” is longitude. Furthermore, N and W are assigned to 40° 47’ 36” and 77° 51’ 36”, respectively. If these coordinates are entered into Google Earth, then

**Figure 1:** Comparing the Everest 1830 and Clarke 1866 reference ellipsoids fitting the Earth’s surface. Scale is highly exaggerated to show the differences in the reference ellipsoids’ positions.
a point near State College, Pennsylvania appears. While Google Earth is cast on the WGS84 datum what happens if the coordinates are, for example, cast on another datum? The location mapped in Google Earth would be incorrect. But, what is a datum and how ‘much’ is incorrect? What follows is a brief overview of horizontal and vertical datums and their importance to mapping activities.

Datums

To be usable, for example in a GIS environment, a coordinate value referencing a position on the Earth’s surface needs to be tied to a datum. Generally speaking, a datum is a base value to which all other values relate. With respect to the Earth, two datums exist: horizontal and vertical.

A horizontal datum fixes a position on the Earth’s surface related to the origin of latitude and longitude. On the other hand, a vertical datum provides a position with respect to an elevation origin such as mean sea level.

Horizontal Datum

Throughout history, the exactness of the Earth’s size and shape has been speculated upon a great deal by many. One outcome has been the development of different Earth models. One model, a sphere, is the simplest in that all points on the Earth’s surface are the same radius from its center. The spherical assumption is usually applied to thematic maps especially at small scales. Of course, the Earth is not a perfect sphere and such an assumption does not provide for a high degree of positional accuracy. Other models such as the reference ellipsoid have been developed to better represent Earth’s shape.

In order to develop a reference ellipsoid, several insights into the Earth were necessary. One insight, discovered by Jean Richter in 1671, was the variation in gravity across the Earth’s surface. Richter’s discovery was integrated by Sir Isaac Newton when, in 1687, he suggested that due to Earth’s gravitational differences and rotation, its shape was better described as an oblate ellipsoid. Also called a reference ellipsoid, it is defined by two parameters: the equatorial and polar radius. With such a model, the polar radius is smaller than the equatorial radius creating a flattening at the poles and a bulging along the equatorial zone.

For illustrative purposes (Van Sickle, 2010, p.9) describes the overall impact of this bulge on the Earth’s dimensions as follows: if the “Earth were built with an equatorial diameter of 25 ft, the polar diameter would be about 24 ft 11 in, almost indistinguishable from a sphere.”

Since the 1800s, dozens of reference ellipsoids were computed that fit the Earth’s shape (particularly local areas) better and provided a higher degree of accuracy in coordinate positioning than a spherical assumption. Table 1 shows several common reference ellipsoids and the parameters that define their mathematical relations. Figure 1 shows the difference between how the Everest 1830 reference ellipsoid ‘fits’ the Earth’s surface of India and the Clarke 1866 reference ellipsoid ‘fits’ the Earth’s surface of North America. Mapping tasks involving a high degree of positional accuracy rely on a horizontal datum that ‘fits’ local areas on the Earth’s surface. Some reference ellipsoids developed more recently, such as the World Geodetic Survey (WGS84), are suitable to model the Earth as a whole.

How much offset exists between the coordinate positions on one reference ellipsoid compared to the other? Assume that 40° 47’ 36” N & 77° 51’ 36” W is defined according to the Clarke 1866 reference ellipsoid. We will transform these coordinates to the Geodetic Reference System 1980 (GRS80). In so doing, Table 2 reports the shift in positions between these two reference ellipsoids.

<table>
<thead>
<tr>
<th>Ellipsoid Name</th>
<th>Date of Inception</th>
<th>Semimajor Axis (meters)</th>
<th>Semiminor Axis (meters)</th>
<th>Flattening</th>
<th>Where Used</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airy</td>
<td>1830</td>
<td>6,377,563.396</td>
<td>6,356,256.91</td>
<td>1/299.3259646</td>
<td>Great Britain</td>
</tr>
<tr>
<td>Everest</td>
<td>1830</td>
<td>6,377,276.345</td>
<td>6,356,075.413</td>
<td>1/300.8017</td>
<td>India</td>
</tr>
<tr>
<td>Clarke</td>
<td>1866</td>
<td>6,378,206.4</td>
<td>6,356,583.8</td>
<td>1/294.9786982</td>
<td>North America</td>
</tr>
<tr>
<td>International</td>
<td>1924</td>
<td>6,378,388.0</td>
<td>6,356,911.946</td>
<td>1/297.0</td>
<td>Various</td>
</tr>
<tr>
<td>Krassovksy</td>
<td>1940</td>
<td>6,378,245.0</td>
<td>6,356,863.019</td>
<td>1/298.3</td>
<td>Soviet Union</td>
</tr>
<tr>
<td>GRS</td>
<td>1980</td>
<td>6,378,137.0</td>
<td>6,356,752.314</td>
<td>1/298.2572221</td>
<td>World</td>
</tr>
<tr>
<td>WGS</td>
<td>1984</td>
<td>6,378,137.0</td>
<td>6,356,752.314</td>
<td>1/298.2572236</td>
<td>World</td>
</tr>
</tbody>
</table>

Table 1: Several common ellipsoids developed for national mapping programs (European Petroleum Survey Group—available at epsg.org accessed April 2014)
ellipsoids. Thus, different reference ellipsoids can produce considerable differences in coordinate positions.

**Vertical Datum**

A vertical datum provides a base value from which elevations or heights are determined. On the Earth a vertical datum expresses a surface of zero elevations. There are two types of vertical datums: tidal and geodetic. A tidal datum is created by averaging water levels over a set time period at a given point (e.g., mean sea level MSL). A geodetic datum provides a network of heights known as benchmarks. The current vertical geodetic datum for the United States is the North American Vertical Datum 1988 (NAVD88). A review of vertical datums and their application to mapping follows.

Heights on the Earth's surface are defined by another Earth model called the geoid. Every point on the Earth's surface is being acted upon by a downward force called gravity. That downward force is also called potential energy and is not the same across the Earth's surface. One way to think about the geoid is to imagine what the Earth's surface would look like if the world's oceans were allow to flow over the land, without any currents or tides, and conform to gravitational pull. As a result, the water's surface (or geoid) is not a regular, but an irregular smoothly changing surface that is influenced by rock density and the Earth's non-spherical shape.

What is height? There are three types of height: orthometric, geoidal, and ellipsoidal. These heights are illustrated in Figure 2. Orthometric height ($H$) is the distance from the geoid to a point on the Earth's surface measured along a plumb line to gravitational pull. The reference surface for orthometric height is a level surface that closely coincides with global MSL (the geoid's surface). Orthometric height is what is commonly associated with elevation of a point on the Earth's surface.

Geoidal height ($N$) is the distance along a normal line from the reference ellipsoid to the geoid. In the coterminous United States, values of $N$ (between the GRS80 reference ellipsoid and the geoid) are about -8 meters to about -53 meters.

Ellipsoidal height ($h$) is the distance along a line normal from the reference ellipsoid to a point on the Earth's surface. Calculating $H$ is simply the difference between $h$ and $N$.

$$H = h - N$$

Height is an important consideration when dealing with data collected via Global Positioning System (GPS). GPS data is considered to be three-dimensional ($X$, $Y$, and $Z$). However, the $Z$ component does not depend upon a direct relation to a gravitational surface. Instead, the $X$, $Y$, and $Z$ coordinates are utilized when calculating geodetic latitude, longitude, and $h$. Then, $h$ can be converted to $H$ so as to be tied into a vertical datum.

**Conclusion**

If your workflow involves handling spatial data then you have experienced problems such as data misalignment, choosing a horizontal datum, or adjusting GPS data to orthometric heights. This article has highlighted the importance of understanding horizontal and vertical datums and how these define a position on the Earth's surface. Correctly assigning a horizontal and vertical datum can mean the difference between spatial data that is both accurate and useable and spatial data that has little value.

**References**


Fritz Kessler is currently Chair of the Geography Department at Frostburg State University where he teaches a mix of courses on cartography, surveying, and research methods. He also teaches an online course on datums, map projections, and grid systems through Penn State’s World Campus. He is the co-author of *Thematic Cartography and Geovisualization.*