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The Definitive Guide to

Coordinate Reference Systems

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If you interact with surveys in any way, you've probably had to answer the question, "What coordinate system are you using?" at least once before.

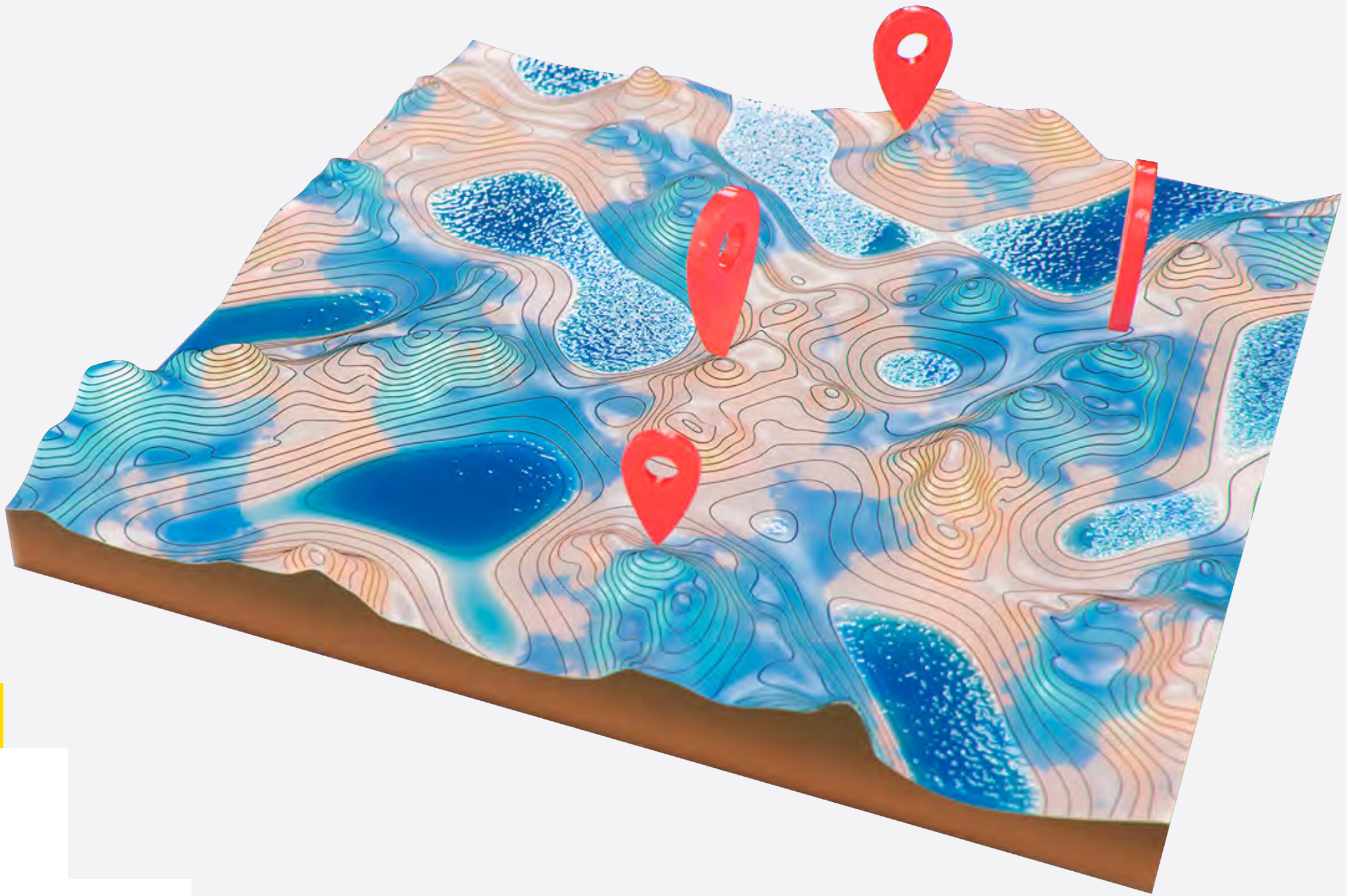
If that question left you speechless, searching for the right answer that never seemed to come, don't worry. You're in the right place.

The truth is, there's a lot to know about Coordinate Reference Systems (CRS) to be an expert. But lucky for you, expertise is not required to gain the full benefit of this data. With this guide, we'll walk you through the key points you should know to get the most out of CRS data and guide you to helpful tools that can make the process much easier.

Let's dig in!

What is a Coordinate Reference System?

A coordinate reference system (CRS), sometimes referred to as a spatial reference system (SRS), is a series of mathematical rules that define the location of a point or feature in an established space.



In other words, they determine what the x, y (horizontal), and z (vertical) coordinates will be. Specifically related to surveys, the "space" is considered a piece of land. That space can be as limited as a single worksite or as broad as the planet Earth.

Why Do We Need Coordinate Reference Systems?

Coordinate Reference Systems allow all types of geospatial information to "speak" the same language. For example, if you were to upload a design file on top of a topographical map that didn't use the same CRS, the data wouldn't be able to communicate clearly with each other, measurements wouldn't line up, and data inconsistencies would abound.

CRS transformations often are necessary when working with disparate data. Let's say you want to compare a historical survey against a present-day survey. If the historical survey was interpreted with an older or different CRS than what you use for your current surveys, you likely will be unable to properly read the two surveys.

Instead, think of a CRS as a language. Using a CRS, then, allows you to "read" a survey map to understand where something is and what its relationship is to other points on the same map.

To help, Propeller developed its own easy-to-use coordinates converter tool. Just plug in a reference coordinate, your current CRS, and the new CRS you want to reinterpret the coordinate through, and Propeller handles the transformation.

Geographic vs. Projected Coordinate Systems

Coordinate Reference Systems are broken down into several categories, including geographic and projected.

Geographic coordinate reference systems define a point on a three-dimensional surface — usually, and for our purposes, the Earth — in relation to its center. Geographic CRSs use degrees of longitude and latitude to describe a location on the Earth's surface, with elevation above or below the surface serving as a third coordinate.

Because surveyors aren't typically dealing with the entire planet as their working surface, they will use a projected coordinate reference system instead.

Projected CRSs define a point on a two-dimensional plane, on which three-dimensional surface has been projected.

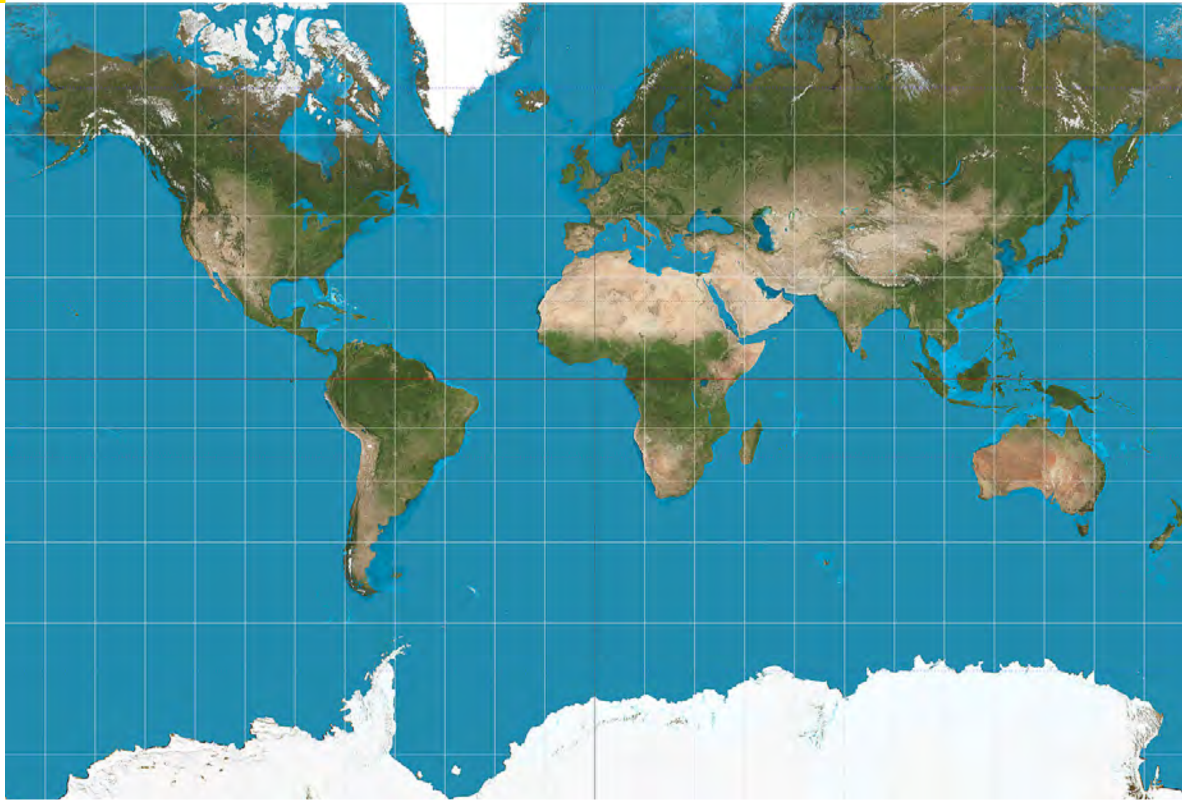
The Problem with Projected Coordinate Reference Systems?

Here's the catch: it's impossible to create an entirely accurate 2D depiction of a 3D surface. If you've ever popped a beach ball and tried to flatten it into a perfect circle, you'd understand why. With this in mind, it's easy to see why 2D models may be distorted in shape, distance, direction, or land area.

Take the most famous projection of the Earth, the Universal Transverse Mercator (UTM), which you probably saw hanging up in a classroom at some point in your education.

Developed by cartographer Gerardus Mercator in 1569, this projection has been used widely for centuries because of its near-perfect accuracy when it comes to direction. Navigators used it to plot consistent straight line courses across the ocean, and basically always ended up where they were expecting.

However, although the UTM excels in its depiction of direction, it fails horribly when it comes to accurate depictions of land mass. According to Mercator, Greenland and Africa are roughly the same size, while, in reality, Africa is roughly twelve times larger than Greenland.



As with most geographic maps, distortions are worse around the poles, which also explains why Antarctica takes up so much space at the bottom of the UTM. In 1871, in a case of cartological shade, Nicolas Auguste Tissot sought to illustrate the inconsistencies of Mercator's and other popularly used projections. The image below depicts "Tissot's indicatrix" atop the UTM. Each ellipse contains the same surface area.

However, distortions to some degree will always play a part in a projection. And while distortions are significantly less pronounced in projections of smaller areas, the lesson remains: only trust maps that were made for your specific purpose.

Ellipsoids, Geoids, and Geodetic Datums

Of the elements that make up a coordinate reference system, none are more fundamental than **datums**. In fact, the term datum is often used interchangeably with "geographic coordinate system" (or a type of CRS used for specifying the location of a point on the earth).

But a datum is only one component of a geographic coordinate system — albeit an indispensable one. To understand the purpose horizontal and vertical datums serve, we must first discuss two related concepts: ellipsoids and geoids.

Let's dispel a common myth about the Earth: it's not a sphere. (At least not perfectly so.)

More accurately, the Earth is an ellipsoid, sometimes referred to as a spheroid. While ellipsoids are round and smooth like spheres, they are not symmetrical when divided in all directions. Because the circumference of the Earth's equator is about 42mi (67km) longer than its meridians, the planet cannot be described as a perfect sphere.

Ellipsoids are defined by their geometric parameters, which include a semimajor axis (the radius of its equator) and semiminor axis (distance from its center to either pole). Geodesists and surveyors use these reference ellipsoids to assign points, angular coordinates, or degrees of longitude and latitude.

But the Earth's surface is not actually smooth like these idealized ellipsoidal models. It has bumps and depressions (technically referred to as undulations), caused by gravity due to the inconsistent density of the planet.

Mountainous areas tend to be denser, and protrude farther out. This explains why, though Denver is not atop a mountain, it is accurately described as the "Mile High City."

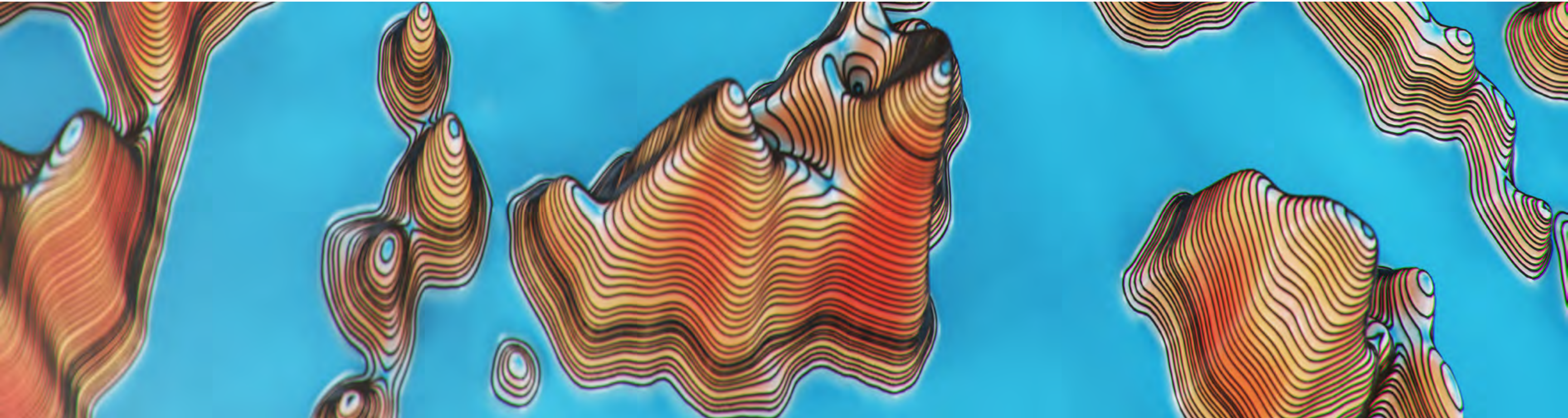
Models that approximate this more accurate shape of the Earth are called geoids. The surface of a geoid represents a Mean Sea Level (MSL), or an "equipotential surface" (a layer where all points are equally affected by gravity). In other words, a geoid's surface is a conjecture of the ocean's surface if tides, wind, and some other factors that restrict its movements didn't exist.

The only factor that effects the MSL's shape is the earth's gravitational field.

So, ellipsoids and geoids define the size and shape of the earth, to varying degrees of accuracy. But that only gets us halfway to our end goal. To be useful, we also need to know which specific model to use and where to place them in space.

That's where datums come in. Horizontal datums take an ellipsoid and assign its center a point of origin relative to the center of the earth. Once the ellipsoid is "pinned" to the earth, we can use the horizontal datum to start assigning angular units of longitude and latitude to different points on the earth's surface.

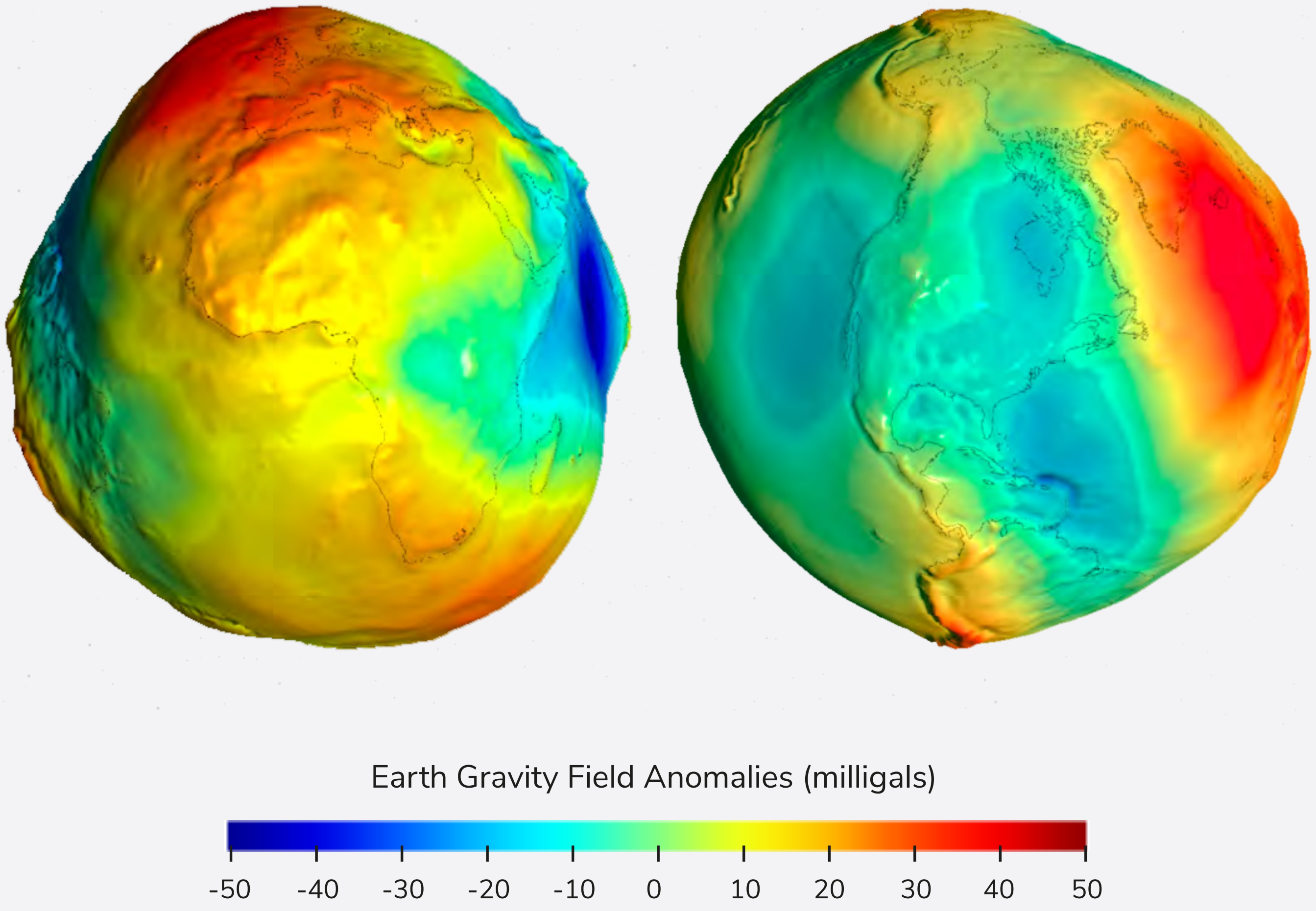
When comparing survey datasets, they need to be referenced through the same datums. Otherwise, the same points in the real world will be assigned different points on your map, and your measurements will be off.



As we just established, the Earth's surface is not uniform. Knowing this, when surveying, you ideally want to use the datum whose ellipsoidal model best fits your area. In other words, you want a local datum.

For instance, in the United States, surveyors use the North American Datum 1983 (NAD 83), which is based on the Geodetic Reference System 1980 (GRS 80) ellipsoid. If you were to use NAD 83 anywhere outside North America, your measurements would be off. All GPS devices reference their readings through the WGS 84, which is a geocentric datum, or one that aims for angular accuracy for the entire planet rather than a single region. The NAD 83 and WGS 84 aren't actually that far off — one meter on average — but the difference is large enough that a datum transformation is necessary for most surveying purposes.

While horizontal datums pinpoint a location on the earth's surface, a vertical datum gets you elevation data. Vertical datums use the surface of a geoid model to establish a zero-point of elevation. Like horizontal datums, there are localized vertical datums. In the U.S., we use the North American Vertical Datum of 1988 (NAVD 88).



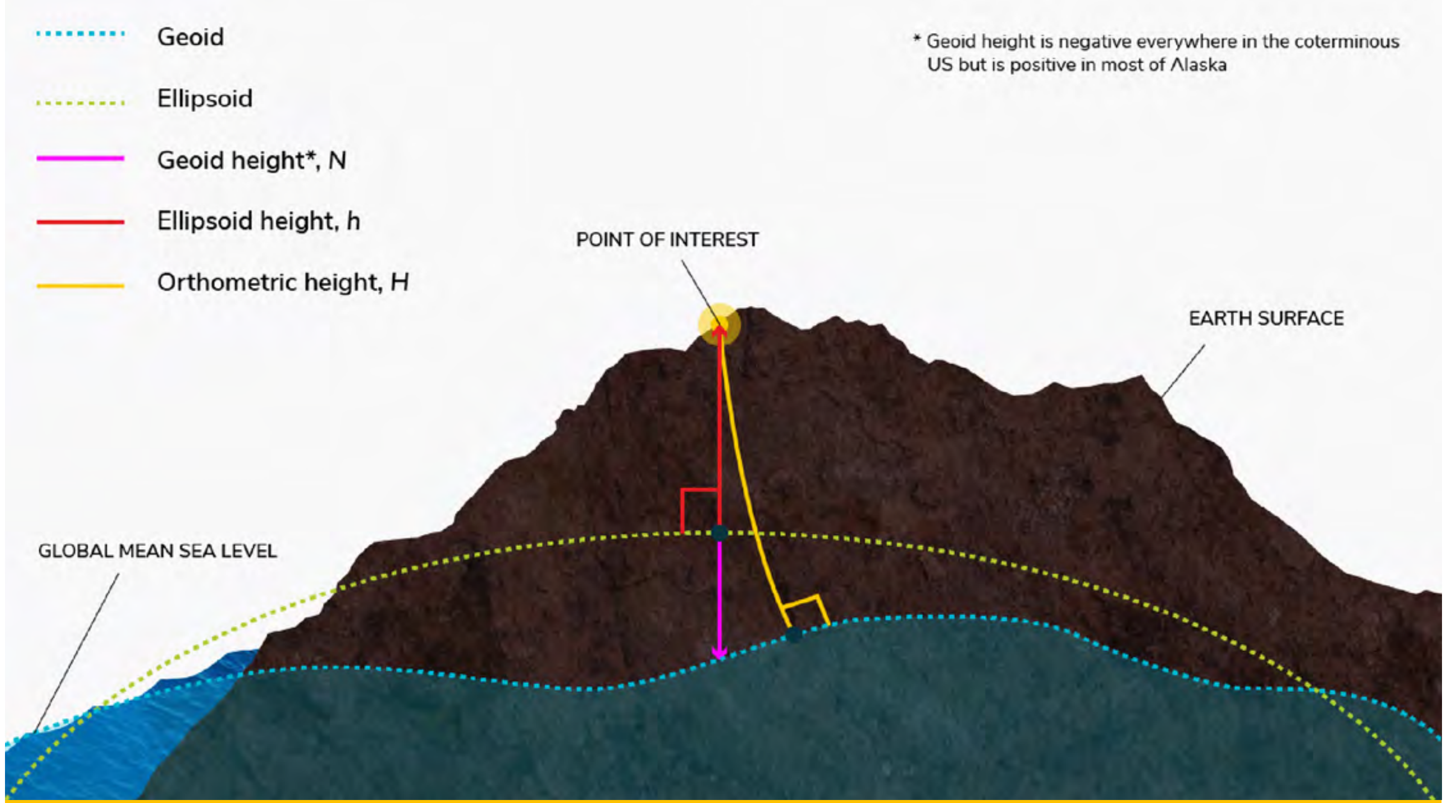
Using Vertical Datums to Calculate Elevation

When it comes to converting elevation data, there are three types of heights to know:

1. **Ellipsoid height (h)** is the difference between the ellipsoid and a point on the Earth's surface. It also is called the geodetic height (not to be confused with geodetic datums). If coordinates were captured with a GPS receiver, the elevation data reference will be the ellipsoid, meaning it has to be transformed to match the more accurate geoid instead.

2. **Geoid height (N)** is the offset value between the reference geoid and the ellipsoid models. This is a constant number, either positive or negative.

3. **Orthometric height (H)** is the distance between a point on the Earth's surface and the geoid. The geoid represents Mean Sea Level. When elevation data is described as "X feet above (or below) sea level, that's referring to orthometric height.



To deliver consistent orthometric heights across your site, Propeller uses your chosen datums and this simple formula: H = h + N.

A Quick Note on EPSG Codes

The EPSG Geodetic Parameter Dataset is the go-to database for CRS and datums. Simplifying things for surveyors and any other scientists who use geographic data, every published CRS includes an EPSG code. When entered into a compliant software (like the Propeller Platform), the EPSG code will load the parameters of its CRS.

These parameters are written in WKT (Well Known Text Representation of Coordinate Reference Systems). Basically, thanks to WKT, surveyors don't have to manually set all CRS components: datums, reference ellipsoids, coordinate grids, and others.

Published vs. Local Coordinate Systems

Published coordinate systems are based on specific global or local parameters. Most major GPS survey equipment will come preloaded with the published coordinate systems and you will need to understand which system is the most suitable for the location you are working in. Of course, a worksite's surveyor could choose to forgo a published CRS altogether and use their own arbitrary coordinate reference system or local grid.

Many sites operate in a local coordinate reference system which measures positions on site relative to a point on the site. This can be for a number of reasons:

1. It may be beneficial to operate in ground coordinates rather than grid coordinates. Why? Ground distances are essentially the horizontal distance as if they were measured with a tape measure, and are based on your actual height above the center of the earth. For example, imagine that you're at the top of a cone and you measure the distance from one side to the other. The distance at the top will be greater than if you measure the distance further down the cone (or closer to the center of the earth). Grid and ground coordinates use the same principles. Ground coordinates are like the top of the cone and always reflect the actual distance measured by a tape on the surface. A grid is a projected surface based on a mathematical model of the surface, which can be higher or lower than the top of the cone. A GPS uses this model, which is why the distance can vary. A scale factor is, therefore, used so that measurements from a rover match measurements on the ground, or vice versa.

2. The site's coordinate system may be isolated from dynamically defined global geodetic systems (e.g., WGS84, NAD83, GDA94), which are sometimes revised due to continental shifts.

3. The magnitude of site coordinates can be drastically smaller compared with a modified state plane or national grid systems, which can extend into the millions of meters/feet.

What's Next?

Understanding the what, why, and how of Coordinate Reference Systems is just the beginning. The next step is to put that knowledge into practice to not only create an accurate and reliable site survey, but also better understand the site data you interact with on a daily basis.

With the help of this guide and our [Coordinates Converter tool](), you'll be well on your way to CRS mastery.

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About Propeller Aero:

Propeller Aero unleashes the full power of data for anyone moving or digging the earth to easily, accurately, and instantly track progress and make faster, safer, and more profitable decisions. Propeller empowers customers to collaborate better, regardless of technical knowledge, streamlining the entire process from bid and design through completion.

More than 2,400 customers in heavy civil construction and resource operations settings across more than 14,000 worksites in over 120 countries trust Propeller to track site progress accurately with 3D visual tools that everyone in the organization can use.

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