Lesson 2: Geodesy and Coordinate Systems

## INTRODUCTION

In this lesson you will learn about Geodesy and Coordinate Systems. The lesson will have examples and information about the aspects that make up coordinate systems. You will learn about the determining factors to consider when creating map projections, deformation and distribution of the projection, and how to determine which map projection to use for a project.

## LESSON OBJECTIVES

By the end of this lesson, you will be able to:

1. Identify elements of geographic referencing systems and map projections.

2. Employ appropriate geographic referencing system parameters and base maps.

3. Explain how different projections, coordinate systems and datums can affect map design and accuracy of map products.

## LEARNING SEQUENCE

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| Required Reading | Read the following:  Geodesy and Coordinate Systems   * Review of Geodesy and Coordinate Systems * Datums * Coordinate Systems * Map Projections * Developable Services * Map Projection Parameters * Great and Small Circles * Map Projection Families * Map Projection Properties * Determining Deformation/Distribution over the Projection * Map Projection Types * Projected Coordinate Systems |
| Assignments | Complete the following assignments:   * Quiz: Geographic Referencing Systems and Map Projections * Lab: Exploring Coordinate Systems and Map Projections |

## INSTRUCTION

## Review of Geodesy and Coordinate Systems

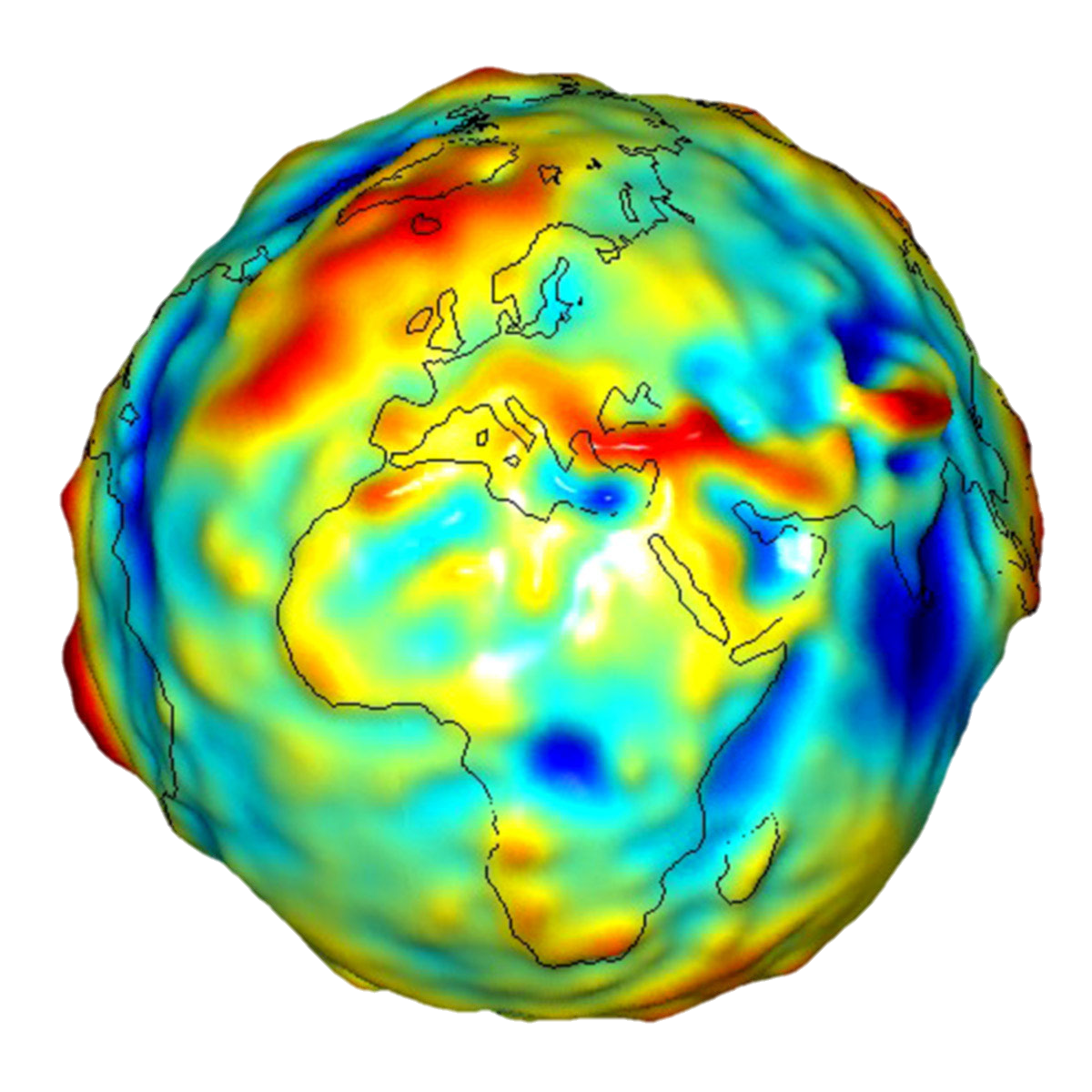
### What is Geodesy?

Geodesy is the scientific discipline that deals with the measurement representation of the earth. Geodesists study the Earth’s gravitational field, motion of the Earth’s crust, tides, and the Earth’s rotation. In order to do this, geodesists have built national control networks that allow them to define and assign coordinates to physical locations on earth.

### Three Approximations of Earth’s Shape

There are three commonly used approximations of the shape of the earth: sphere, ellipsoid, and geoid. The sphere is the simplest approximation of the earth’s shape as it is defined by a single radius. The ellipsoid is closer to the earth’s shape as defined by semi-major and semi-minor axes. The geoid is the closest approximation of the earth’s shape based on gravity measurements that help define global mean sea level. The reasons why the sphere and ellipsoid are still used are that they are much easier to use for calculations and when defined properly can be exceptionally accurate.

Sphere Ellipsoid Geoid



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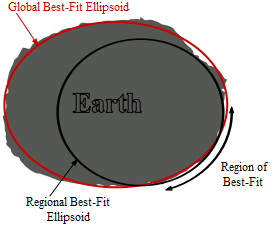
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### Ellipsoids

The ellipsoid is the most commonly used of the three approximations of the earth’s shape today. There is not a single ellipsoid that fits earth well; therefore, there have been many official ellipsoids throughout the 19th and 20th centuries. Different ellipsoids were adopted because different measurements were used in different countries when defining these ellipsoids, and geodetic surveys were isolated by large bodies of water. Because of this, and ellipsoid created by one country may approximate that portion of the earth very well, but may not be a suitable approximation for another portion of the earth.



## Datums

### What are Datums?

According to the National Geodetic Survey, a datum is a set of constants specifying the coordinate system used for calculating coordinates of points on earth. Datums serve as starting points of reference for surveying and mapping as they link the physical earth to a mathematical coordinate.

A datum is a reference surface for measuring locations on the earth. A datum has two major components: the specification of an ellipsoid, which is an ellipsoid that has been surveyed and defines the origin and orientation of latitudes and longitude lines. We cannot assign any coordinates to a location without first specifying a datum and linking that datum to the shape of the earth through field measurements.

### Common Datums

There are three common datums that you will use in GIS: North American datum of 1927 (NAD 27), North American datum of 1983 (NAD 83), and World Geodetic System of 1984 (WGS 84).

#### NAD 27

The first datum we will discuss is the North American datum of 1927 also referred to as NAD 27. The NAD 27 datum is based on the Clarke 1866 ellipsoid which holds a fixed latitude and longitude in Kansas. The locations were adjusted based on about 26,000 measurements across North America. Quite a bit of GIS data is still available in NAD 27, however, more recent data should use North American datum of 1983.

#### NAD 83

The North American datum of 1983, or NAD 83, is the successor of NAD 27, and uses an earth centered reference ellipsoid rather than a fixed station in Kansas. Additionally, 250,000 points were measured to adjust the latitude and longitude locations.

It is worth mentioning that it is okay to use NAD 27 or NAD 83 data, however, when performing analysis you should convert all the data into a single datum for analysis purposes.

#### WGS 84

The third common datum is the World Geodetic System of 1984 commonly referred to as WGS 84. WGS 84 is based on satellite measurements and the WGS 84 ellipsoid which is similar to another ellipsoid named GRS 80. The major difference between the WGS 84 ellipsoid and the NAD 27 and NAD 83 datum is that the WGS 84 data has worldwide coverage, where NAD 27 and NAD 83 should only be used in North America. You should also note that the WGS 84 datum is used by the GPS system to report latitudes and longitudes.

Datums are not static and often see updates and adjustments throughout time. In fact, both NAD 83 and WGS 84 have been updated multiple times. Therefore it is very important that you read the documentation of the datasets that you are using in your GIS to determine exactly which datum was used in determining locations.

## Coordinate Systems

### 3D Coordinate Systems

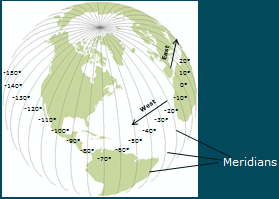
As it pertains to Earth, we use 3-D coordinate systems which represent a sphere such as the earth. The important thing to note about the 3-D coordinate systems that we are going to discuss in this section is that it will not ignore the curvature of the earth, which makes it ideal for displaying locations, and measuring distances across long distances were the curvature of the earth will become a factor.

The 3-D coordinate system that we are going to discuss is going to use two angles of rotation commonly known as latitude and longitude, and a radius to specify the location. The angles of rotation will determine whether the location is north or south of the equator or east or west of the Prime Meridian and the radius will specify how far from the center of the earth that location is.

#### Longitude

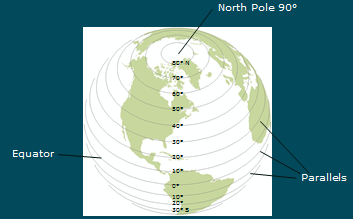
Longitude, also known as Meridian, is the angle of rotation measured east and west around the globe. What may be confusing is that the lines of longitude run north-south from the North Pole to the South Pole. Lines of longitude will vary from positive 180° east to -180° west measured relative to the line of longitude of 0° which is known as the Prime Meridian.

The Prime Meridian runs through Greenwich, England. Lines of longitude west of Greenwich, England up to and including 180° are represented as a negative number or as a Western longitude. Lines of longitude east of Greenwich, England up to, and including 180°, is represented as a positive number or as an Eastern longitude.



#### Latitude

The second angle of rotation is known as latitude and is also referred to as a parallel. Parallels measure north to south on the globe, and the lines run in parallel to each other east and west from the North Pole to the South Pole. The equator is the latitude of 0°. Lines of latitude measure from positive 90° north, which is located at the North Pole, to -90° south, which is located at the South Pole.



### 2D Coordinate Systems

The 2-D Cartesian coordinate can represent many possible locations at many possible scales, and it is so flexible you can even create your own. However, there are two common representations that are widely used in North America, and the world. The first is the State Plane Coordinate System and the second being the Universal Transverse Mercator Coordinate System or UTM system.

#### State Plane

The state plane coordinate system is a set of 126 geographic zones that cover the United States of America. Each zone is designed specifically for the region of the United States of America that it covers. It is useful because it allows for simple calculations and is reasonably accurate within each zone. In the state plane coordinate system coordinates are always positive inside each zone. The state plane coordinate system can be based off of NAD 27 and NAD 83 datums, and the coordinates are represented and measured in feet.

Each state may have multiple state plane zones but this is not required. Each zone is strategically placed to minimize the amount of error within each zone. Additionally, each zone provides a common coordinate reference for horizontal coordinates over areas such as counties while limiting error to specified maximums. Depending on the shape of the state, the state plane zone can be based on two types of map projections, the Lambert Conformal Conic, or the Transverse Mercator.

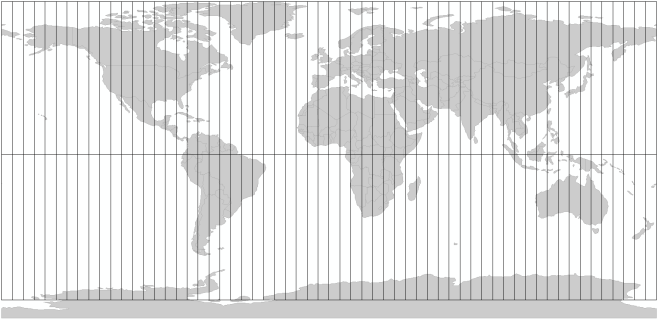
Provided below is an illustration of the state plane zones in the 48 lower contiguous states of the United States of America. Notice that most states have multiple zones and that zones typically either run north to south, or east to west. Also note that most of the smaller states, particularly in the New England area, only have one state plane zone covering the entire state, while larger states such as California and Texas, have multiple zones so that the error can be minimized throughout the state. A notable exception to this is Montana. It is a large state but only has a single zone. State plane zones are typically designated with the name of the state followed by a section indicator, such as North, Central, and South, or combination of those, or, West, Central, and East. A notable exception is California which specifies each zone using a different number.



#### Universal Transverse Mercator Coordinate System UTMCS

The Universal Transverse Mercator Coordinate System (UTMCS) is a worldwide 2-D coordinate system that splits the world into 60 zones. The Universal Transverse Mercator Coordinate System is useful because it provides for simple calculations and manages error within each zone. Unlike the state plane coordinate system which is measured in feet, the universal transverse Mercator coordinate system is specified and measured in meters.

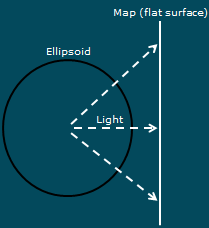
This is an illustration of the state plane zones covering the world from 80° South 84° north. Note the line running along the equator, which splits as zones into north, and south.



## Map Projections

### What are Map Projections?

Defined, a map projection is a systematic rendering of locations from the curved earth surface onto a flat map surface. This allows us to flatten the curved surface onto a flat surface such as a piece of paper, or computer screen. The reason why we employ map projections is because globes are not very portable, or practical to use in some cases. Therefore we use map projections to flatten the earth into a map.

This basic illustration displays the concept of a map projection. The map projection is broadly composed of three parts, the ellipsoid, which models the shape of the earth, a light source which is used to project features on the earth surface, and a developable surface commonly a flat piece of paper onto which the Earth’s features are projected, and flattened to be used as a map.

## **Developable** Surfaces

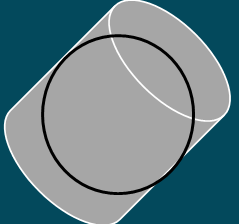
### What is a Developable Surface?

A developable surface is a geometric surface on which the curved surface of the earth is projected; the end result being what we know as a map. Geometric forms that are commonly used as developable surfaces are planes, cylinders, cones, and mathematical surfaces.

No matter which developable surface is used to create a map the basic idea remains the same. The features of the curved earth are projected onto one of the four geometric forms to produce a flat map.

Plane Cylinder Cone Mathematical

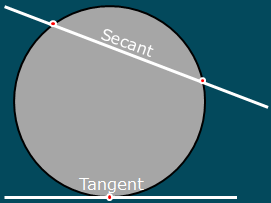
## The way in which an ellipsoid and developable surface interacts with each other is to place the ellipsoid in different locations and different rotations is to gain a desired view at map properties. In this illustration the blue circle is an ellipsoid representing the earth. The triangle represents a cone although we are representing it in 2-D. The idea is that the developable surface can be placed on top of the ellipsoid as a hat, or pulled down through the surface of the earth, and even rotated side to side, or forwards and backwards to create the desired view that we are looking for in a flat map.

### Interaction

These developable surfaces will interact in a few different ways with the ellipsoid. Generally, the developable surfaces will touch the ellipsoid in either two places which creates two secant lines or at a single location and creates a single tangent line. In the illustration shown the tangent line is touching the ellipsoid of the South Pole which should give us a polar view of the earth.

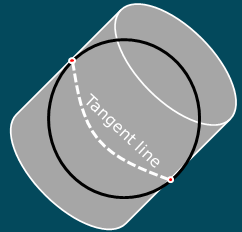
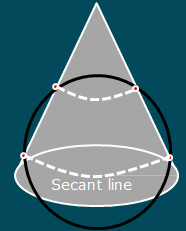
The secant intersection is intersecting the earth at two locations which provides us with an abnormal view of the northern portion of the ellipsoid. Both types of interactions are correct as they depend on the purpose of the map and the way in which we want to portray the earth on a flat map.



Two secant lines, one point or tangent line

To further illustrate the idea of a tangent and secant intersection, two more illustrations are provided. For the tangent interaction there is a line that can be drawn around the earth at its widest point that is perpendicular to the point tangents. This is known as the tangent line. For secant interactions two lines are drawn following the earth’s curvature between the secant intersection points.

**Tangent** **Interaction Secant Interaction**

## Map Projection Parameters

### Project Parameters

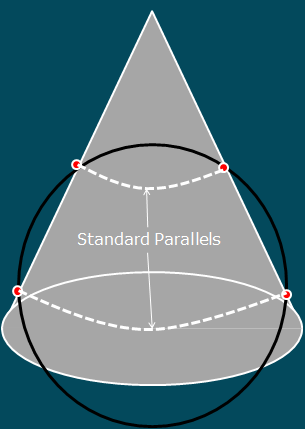
There are five map projection parameters that are going to be discussed in this section. They are: standard points and lines, projection aspect, central Meridian, latitude of origin, and light source location. Together these five map projection properties allow an individual to selectively display and distort the earth to create a map that is suitable based on need. The lesson will start with standard points and lines and continue on with details covering each of the additional four map projection parameters.

### Standard Points and Lines

Defined, a standard point and line is a point or line of intersection between the developable surface and the spheroid or ellipsoid. In the case of a secant intersection, there will be two standard lines that would define where the developable surface intersects with the spheroid.

If the developable surface happens to intersect the spheroid along a line of latitude it is known as a standard parallel. Additionally if a standard line falls on a line of longitude exactly it is known as a standard Meridian. When defining a map projection you must define the standard points and lines. It is not uncommon to have a map projection follow a standard parallel or standard Meridian.

In this illustration the cone is in a normal aspect and with the secant intersection, the secant intersecting lines follow parallels. Therefore they are both known as standard parallels.



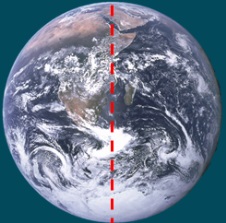
### Importance of Standard Points and Lines

The reasons why standard points and lines are important are because the corresponding places act or along the standard point to lines will have no scale distortion. That means that where the developable surface intersects with the spheroid there is little to no distortion on our flat map. The further away from the standard point or lines the greater the distortion or deformation that will occur on the map. Secant intersection between the developable surface and the spheroid can help minimize distortion over a large area by providing more control than a tangent intersection at a single point or line. Therefore placement of standard points and lines is one of the most important parameters to consider when defining a map projection.

### Project Aspect

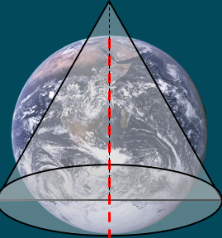
The next projection parameter to discuss is the projection aspect. A projection aspect is the position of the projected graticule relative to ordinary position of the geographic grid on earth. What that means is that if the developable surface’s vertical axis coincides with the vertical axis of the earth this defines a normal aspect. Should the vertical axis of the developable surface differ from the vertical axis of the earth this would be an abnormal aspect.

### Globe Normal Axis



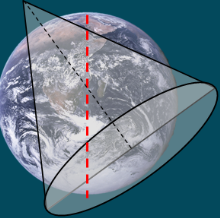
This illustration displays the normal axis of the globe, which runs from the North Pole through the center of the Earth to the South Pole.

### Normal Aspect



This illustration shows a cone developable surface at a secant intersection with the earth. The vertical axis of the cone, displayed as a blue line, coincides with the vertical axis of the earth displayed as a red dotted line which is considered a normal aspect.

### Non-Normal Aspect



This illustration shows a non-aspect. Note that the vertical axis of the cone does not coincide with the vertical axis of the earth thus creating a non-aspect.

### Central Meridian

The next projection parameter to discuss is the Central Meridian. The Central Meridian defines the center point of the projection. That means that this is the Meridian, or longitude line, that displays in the center of the map. Essentially this allows you to rotate the earth about the vertical axis to determine what portion of the earth you want to have in the center of the map.

### Latitude of Origin

Related to the Central Meridian is latitude of origin. Latitude of origin is the latitude that defines the center of the projection. That means that this is the latitude that will be in the center of the map projection. Changing the latitude of origin moves the projection about the horizontal axis to determine which portion of the earth will be shown in the middle the map.

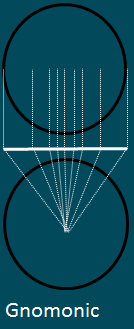
### Light Source Location

The light source location map projection parameter is the location of the hypothetical light source in reference to the globe being projected. Remember that there are three parts of a map projection: ellipsoid, the light source, and the developable surface. The light source is what projects the surface of the earth onto the developable surface and there are three primary positions in which we can place the light source.

The three primary positions of light sources are gnomonic, stereographic, and orthographic.

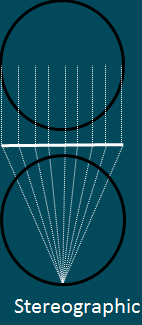
#### Gnomonic

In the gnomonic light source position the light source is placed at the center, or core, of the earth. The light is then projected through the earth’s surface and projects the landmasses onto the developable surface. In the illustration, the earth is the bottom circle, the lines are the light source, and the solid white line is the developable surface, in this case a plane. The top circle and the dotted lines represent where the earth will be compressed, or stretched, based on the position of the light source. In the case of the gnomonic light source, looking at a polar projection, locations at the center of the earth are held closer to true. However the locations towards the extremities are elongated as they are stretched out to meet the developable surface.



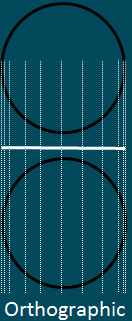
#### Stereographic

In the stereographic projection the light sources are placed at the opposite side of the earth from where the developable surface has its secant or tangent intersection. In this case we see a less severe differential between where the earth is compressed and elongated, but no location is clearly free from distortion.



#### Orthographic

In the orthographic position the light is placed at a theoretical infinite distance from Earth opposite from the point of intersection or tangency. This allows formidable distortion in the center the projection however there is significant compression at the extremities of the map.

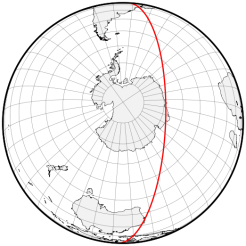


## Great and Small Circles

### Great Circle

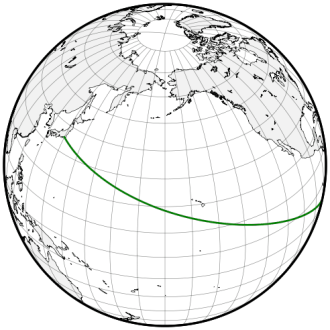
A great circle is a circle that results when a plane intersects the earth going through the center effectively dividing the earth into two equal parts. Based on this definition, all meridians and the equator are considered to be great circles as they all divide the earth into two equal halves.

An arc segment of a great circle is the shortest path between two points on a spherical surface. Therefore, to determine the shortest distance between two points on earth you would first construct a great circle and then calculate the distance along that segment.

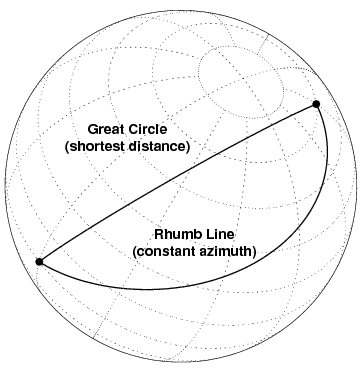
### Small Circle

A small circle is a circle the results when a plane intersects the earth but does not go through the center effectively dividing the earth into two equal parts. Based on this definition of a small circle, all parallels, except the equator, and other lines that do not pass through the center of the earth are small circles. A small circle is not the shortest distance between two points on the spherical surface even though it may appear to be.

### Rhumb Line

A Rhumb Line is a curve that crosses each Meridian at the same angle. This is also known as a loxodrome. Rhumb lines are useful because they are easier for navigation because a rhumb line follows a constant bearing or azimuth. While the Rhumb line is easy to use for navigation it does require that you follow a longer distance in the shortest possible distance which would be a great circle.



### Importance of Great and Small Circles

There are three important reasons that you should know about circles. First, on an azimuthal projection all lines drawn through or to the center of the projection are great circles. Second, on an azimuthal projection all lines not drawn to the center are considered small circles. And third on a gnomonic azimuthal projection all lines drawn are great circles.

These three points illustrate that even though the map user may draw a straight line on a map projection, it may not represent the shortest distance between two points. Therefore it is important that you consider how different map projections portray small and big circles and what implications that will have for your map user.

## Map Projection Families

### Azimuthal Family

The azimuthal map projection family, also known as the Planar or Zenithal map projection family is when a spheroid is projected onto a flat plane. Based on this interaction between the spheroid and a developable surface we see deformation outward a series of concentric bands from the center. The azimuthal family of map projections is commonly used to display larger scale maps and Polar Regions of the earth. The azimuthal map projection family has three aspects: polar, which is considered the normal aspect, oblique, and equatorial.

### Polar Aspect



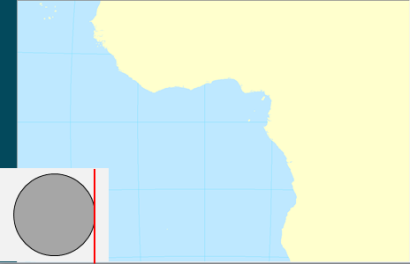
This is an illustration of an azimuthal map projection with a polar aspect. The plane’s pointed tangency is the North Pole, and the earth is then unfolded onto the plane which causes deformation in a radial pattern way from the North Pole.

### Oblique Aspect (Mid-Latitudes)



This is an illustration of an azimuthal map projection with an oblique aspect along the mid-latitudes of earth centered over Europe. Here, the developable surface’s pointed tangency is centered over Europe, and the earth is folded out onto the plane.

### Equatorial



This is an illustration of an azimuthal map projection within equatorial aspect. The developable surface’s pointed tangency is on the equator.

### Cylindrical Family

The second map projection family we will discuss is the cylindrical family. The cylindrical family projects the spheroid onto a cylinder. The spheroid is deformed and increasing bands of exaggeration towards the outer edges of the map plane. The cylindrical map projection family is commonly used to display the entire world, or medium and large scale mapping. One unique characteristic of the cylindrical family is that all parallels and meridians intersect at 90° angles.

### Miller Cylindrical Projection

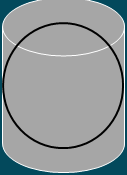


This is an illustration of the Miller cylindrical projection. In this projection, the center of the cylinder touches the equator.

### Cylindrical Aspects

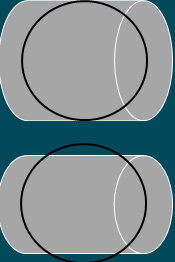
There are three cylindrical aspects: equatorial, just consider this the normal aspect, transverse, which is also known as the polar aspect, and the oblique aspect.

### Equatorial (normal)



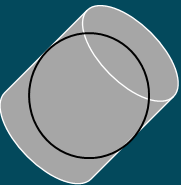
This is an illustration of the equatorial aspect for the cylindrical family of map projections. For this aspect, the line of tangency follows the equator.

### Transverse (polar)



Here we see the transverse, or polar, aspect for the cylindrical projection. In the case of the transverse aspect, the cylinder can have a single line of tangency following a Meridian from North to South Pole, or a secant intersection for the cylinder is still centered over the pole.

### Oblique

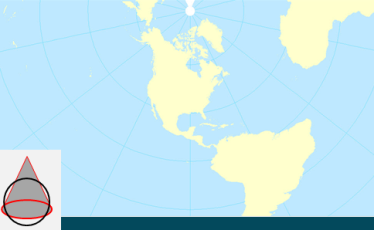


In the oblique aspect, the line or lines of intersection between the developable surface and the spheroid touch the Earth between the equator and the poles.

### Conic Family

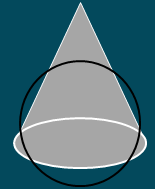
The third map projection family is the conic family. In the conic family the developable surface is a cone onto which the spheroid is projected. We see deformation and concentric bands parallel to the standard parallels of the map projection. The conic family is commonly used to display areas of earth having a greater east-west extent.

### Conic Projection



This illustration shows how the cone developable surface interacts with the spheroid. In this case, the cone is pushed through the surface of the earth so that it has two secant lines of intersection. The lines of intersection follow parallels which reduce distortion in the east-west direction.

### Conic Aspects



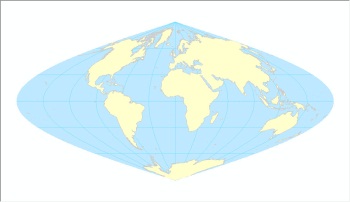
With respect to aspects, the conic map projection family is typically presented in the normal aspect where the axis of the cone is in line with the axis of the spheroid.

### Mathematical Family

The final map projection family we will discuss is the mathematical family. To create a map projection of the mathematical family the spheroid is projected onto a mathematical surface that is not a cone, plane, or cylinder. Deformation can vary quite widely depending on the shape of the developable surface.

Additionally, since the developable surfaces in this mathematical family can vary so greatly, there is no common map purpose that is used with the mathematical family of map projections. In some cases developable surfaces in the mathematical family of map projections may resemble cylinders, cones, or planes that have been slightly deformed or warped for a specific need. In these cases the developable surfaces may be referred to as pseudo-cylindrical, pseudo-conic, or pseudo-azimuthal.

### Sinusoidal



This is an illustration of a mathematical developable surface known as a sinusoid.

### Hammer-Aitoff



This is a map projection known as the Hammer-Aitoff which is a map projection in the mathematical family.

## Map Projection Properties

### Map Projection Property Defined

A map projection property is an alteration of area, shape, distance, and direction on a map projection. These map projection properties exist because the conversion from a three dimensional object, such as the earth, to a two-dimensional representation, such as a flat paper map, requires the deformation of the three-dimensional object to fit onto a flat map. The three-dimensional spherical surface is torn, sheared, or compressed to flatten it onto a flat developable surface.

### Four Map Projection Properties

These map projection properties are area, shape, distance, and direction. These four map projection properties described for facets of a map projection that can either be held true, or be distorted.

#### Area and Shape

Area and shape are considered major properties and are mutually exclusive. That means, that if area is held to its true form on a map, shape must be distorted, and vice versa.

**Major Properties**

Area Shape

Mutually Exclusive

#### Distance and Direction

Distance and direction, on the other hand, are minor properties and can coexist with any of the other projection properties. However, distance and direction cannot be true everywhere on a map.

**Minor Properties**

Distance Direction

Cannot exist everywhere on a map

### Equal Area Map Projection

The equal area map projection, also known as the equivalent map projection, aims to preserve the area relationships of all parts of the globe. You can easily identify most equal area map projections by noting that the meridians and parallels are not at right angles to each other. Additionally, distance distortion is often present on equal area map projections and the shape is often skewed.

Even with the distortion of distance and shape, equal area map projection is useful for general quantitative thematic maps when it is desirable to retain area properties. This is especially useful for choropleth maps, when the attribute is normalized by area. Holding area properties to be true allows for an apple to apple comparison of density between different enumeration units such as counties. Two types of equal area map projections include: Cylindrical Equal Area and Hammer-Aitoff.

#### Cylindrical Equal Area

The cylindrical equal area map projection is an example of an equal area, or equivalent map projection, which aims to keep the areal relationships of all parts of the globe correct.



#### Hammer-Aitoff

### A second example of an equal area projection is the Hammer-Aitoff map projection. Again, like the cylindrical equal area projection, this map projection aims to hold areas true. Also note that on this map projection, the parallels and meridians do not intersect at 90° angles, which is a hint that lets us know that this may be an equal area projection.

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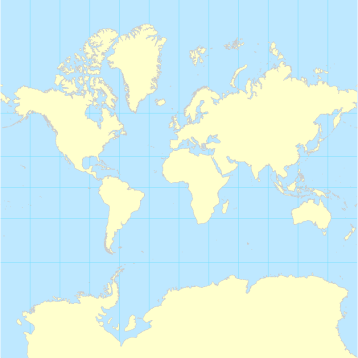
### Conformal Map Projections

Conformal map projections, also known as orthomorphic map projection, preserves angles around points and shapes of small areas. Additionally it allows for the same scale in all directions to or from a single point on the map.

Conformal map projections can usually be identified by the fact that meridians intersect parallels at right angles, areas are distorted significantly, its’ small scales, and the shapes of large regions may be severely distorted.

Even with the potential for large shape distortion conformal map projections are useful for large scale mapping and phenomena with circular radial patterns such as radio broadcasts for average wind directions.

The Mercator projection, perhaps the most famous of all map projections, is a conformal map projection that preserves shape. However notice the massive amount of distortion in the lower latitudes towards the South Pole and the northern latitudes near the North Pole. Also note that the parallels and meridians intersect at 90° angles.

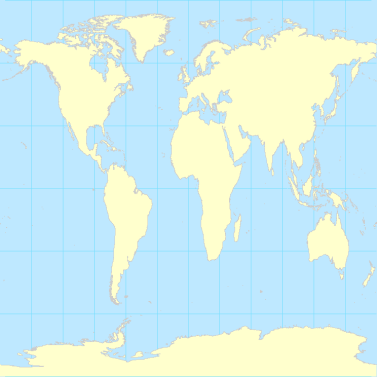


### Equidistant Map Projection

The third map projection family is the equidistant map projection which aims to preserve great circle distances. That means a distance can be held true from one point to all other points or from a few select points to others but not from all points to all other points. It is also important to note the scale is uniform along these lines a true distance from the select points on the map. Identifying marks of the equidistant map projection are that they are neither conformal nor equal area, and look less distorted. Equidistant map projections are useful for general purpose maps and Atlas maps.

An example of an equidistant map projection is this equidistant cylindrical map projection. Notice that compared to the conformal map projection there is less distortion at the North and South Poles, and the shapes do not look overly distorted.

**Equidistant Cylindrical**

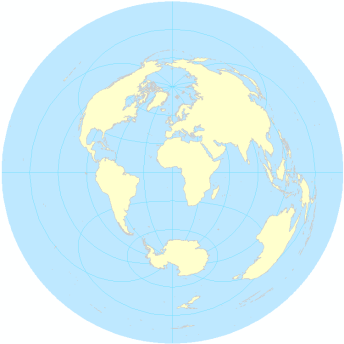


### Azimuthal Map Projection

The azimuthal map projection, also known as the true direction map projection, preserves direction from one point to all other points in the map. It is important to note that direction is not true between non-central points. Direction is only true when measured to or from the specific points chosen to have true direction. Azimuthal map projection is most useful for preserving direction two or one from point, often used for navigation.

The azimuthal equidistant map projection is an example of a true direction map projection that also holds distance to be true. While not all azimuthal map projections look like this, this particular map projection allows you to measure across the poles and around the world to determine true distance and direction from a single point.

**Azimuthal Equidistant**



### Combined Map Projections

As seen on a few example map projections previously we can combine map projection properties onto a single projection. For example an equal area map projection can also combine parts of it azimuthal map projection. Conformal can combine with azimuthal, equidistant can combine with azimuthal, and azimuthal can combine with equal area, conformal, and/or equidistant.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | **Equal Area** | **Conformal** | **Equidistant** | **Azimuthal** |
| **Equal Area** | **--** | **No** | **No** | **Yes** |
| **Conformal** | **No** | **--** | **No** | **Yes** |
| **Equidistant** | **No** | **No** | **--** | **Yes** |
| **Azimuthal** | **Yes** | **Yes** | **Yes** | **--** |

**Yes** denotes map projections can be combined.

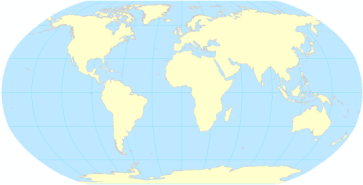
**No** denotes that map projections cannot be combined.

### Compromise Map Projection

There is another map projection family that does not try to hold a single map projection property true. This map projection family is known as the minimum error, or compromise map projection. The goal of the compromise map projection is to simultaneously minimize all for map projection properties, but may not hold any of the four map projection properties as true. The compromise map projection is useful for general geographic cartography.

An example of a compromise map projection is the Robinson map projection. It does not greatly distort any of the four map projection properties nor does it hold any of the four properties true. However what is nice about the Robinson map projection is that it does a reasonable job of showing the true shape, distance, direction, and size of the features of the earth.

**Robinson Map**



## Determining Deformation/Distribution over the Projection

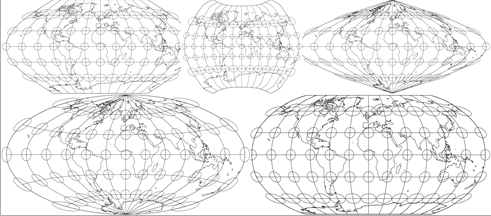
### Tissot’s Indicatrix

A common method used to determine deformation on a map projection is called Tissot’s indicatrix. As we know all flat maps distort shape, area, direction, or length when displaying features of a three-dimensional object such as the earth. Tissot’s indicatrix helps to quantify the distortion and projection properties shown on the map projection.

Tissot’s indicatrix is composed of infinitely small circles centered at points on the earth. The earth is then projected onto a map using a map projection and we consider the shape of the circles after projecting the map to determine the deformation and distribution of error throughout the map.

To gain a better understanding of of Tissot’s indicatrix look at the image with five map projections. Remember that the circles were all originally the same size and were perfect circles. We will interpret Tissot’s indicatrix by seeing what happens to the circles when the earth is projected.

**Tissot’s Indicatrix**



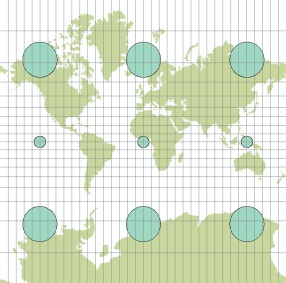
### Interpreting Tissot’s Indicatrix

As you learn how to interpret Tissot’s indicatrix consider how the circles change on an equal area and conformal map projection. On an equal area map projection the circles will be transformed into ellipses but the area of the ellipses will be the same as the area of the original circles. That means although they will change shape they will not change in size. On a conformal map projection the circles will continue to be perfect circles but their size will vary over the map.

#### Conformal Projection Property

The lesson will show a few common map projections so you can see how Tissot’s indicatrix performs. On the Mercator map projection which is a conformal map projection the perfect circles would continue to remain circular however they will be larger or smaller than the original circle size. This is due to fact that the conformal map projection property keeps shape true but must distort size as shape and size are two major map projection properties, and are mutually exclusive.

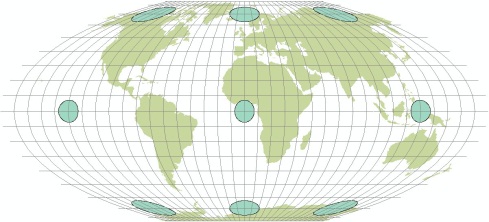
**Mercator Projection**



#### Equal Area Projection Property

Consider the flat polar quartic projection and how Tissot’s indicatrix performs on it. As the flat polar quartic projection is an equal area projection circles will not have the same shape as a perfect circle; however, they will have the same area as the original circle. As we see on this map projection the circles roughly have the same size although we are still seeing some areal distortion towards the North and South Poles.

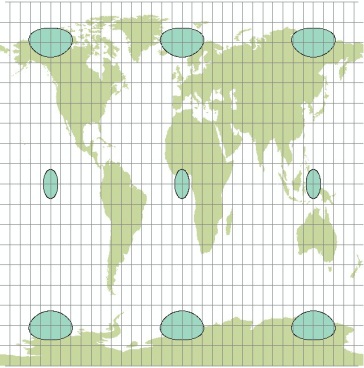
**Flat Polar Quartic Projection**



#### Equidistant Map Projection

On an equidistant map projection such as the equidistant cylindrical projection, where distances are true between two points, the circles are formed into different shapes throughout the map projection. This tells us that this map projection distorts both shape, and size, however, we are not able to immediately tell that this is an equidistant map projection based solely on the size and shape of the circles.

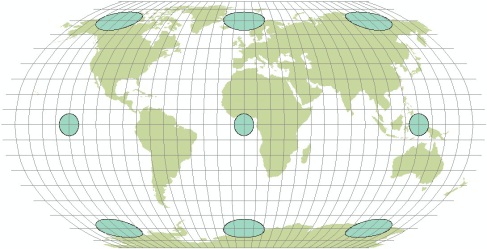
**Equidistant Cylindrical Projection**



#### Aphylactic Map Projection

On an aphylactic map projection, which is another way of referring to a compromise map projection, we do not have perfect circles anywhere on the map; however, the distortion is not severe anywhere on the map. Again this is because the aphylactic map projection distorts all four properties but no one property is distorted much greater than the other.

**Robinson Projection**



## Map Projection Types

### Which map projection do I use?

In order to choose the optimal map projection for your map there are many things that you must consider.

### Projection Properties

* You must consider the projection properties and whether those properties are compatible with the purpose of your map. For instance, if you want users to compare density across the globe you would want to choose an equal area map projection so that areas are kept true allowing users to do a true comparison with respect to density.

### Deformational Patterns

* You also need to consider the deformation patterns of the map projections. Some spatial phenomena are better represented using certain deformation patterns.

**Projection Center**

* You will need to consider where you wish to center the projection. Typically you center the projection over the area that is of interest to the map user.

### Familiarity

* You should also consider how familiar your map users are to the map projection. Depending on your audience they may have a preconceived notion of what a map looks like. Then if you show them a complex mathematical map projection it may confuse the user too much and they may not be able to utilize your map to its fullest.

### Software Support

* You should consider software support if you are making a virtual map. Not all GIS and mapping software support the same map projections; therefore, if you are sharing your produced map you should make sure that the recipient has access to software that supports the same map projection of your map. If your map is part of a larger map series then the map projection you choose for your map should allow the map to have the same look and feel of the other maps for continuity and ease of use.

Note: The rest of this lesson will discuss broad recommendations for what types of map projections you should use for particular situations. The discussion will not be exhaustive, nor must it be followed exactly. It is a good exercise and is often expected for a cartographer to render the map using many different map projections including changing properties to suit their needs before choosing the final map projection.

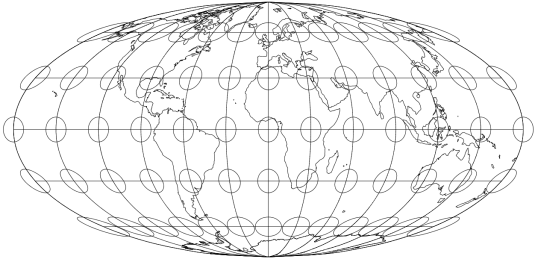
### Recommended Map Projections for World Projections: Equivalent

Equivalent map projections are recommended for world projections. Review the following types of equivalent map projections to become familiar with what their map projections entail.

#### Mollweide

The Mollweide map projections are useful for mapping world distributions as it does a good job of keeping relative sizes in check about the equator and mid-latitudes, however does distort greatly at the poles as can be seen with Tissot’s indicatrix.

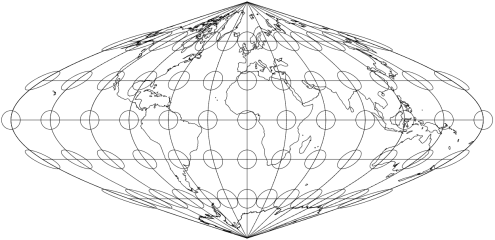
### Mollweide



#### Sinusoid

The sinusoid all map projection is also useful for mapping world distributions. Like the Mollweide map projection it too does a reasonable job of keeping relative size intact around the center of the map and between the middle latitudes. However, as you approach the extremities of the map, distortion becomes quite great.

### Sinusoid



#### (Aitoff-) Hammer

The Aitoff-Hammer map projection is useful for mapping world distributions and excels at reducing the shape distortion at the extremities. The trade-off is that it does not hold the shape as well across the entire projection as the previous two map projections.

**(Aitoff-) Hammer**

### 

#### Goode’s Homolosine

## The Goode’s Homolosine map projection is interesting because it is an interrupted map projection that maximizes distortion over bodies of water and minimizes distortion over landmasses. One of the most negative aspects of using a good small sign map projection is that it is unfamiliar to many users and may confuse them.

### Goode’s Homolosine

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### Recommended Map Projections for World Projections: Minimum Error

## Minimum error map projections are also recommended for world projections. This section will focus on the various types of minimum error map projections.

#### Robinson

## The Robinson map projection is a good choice for mapping the world. It does a reasonably good job of maintaining equal area and equal shape across the earth but it does distort once you reach the extremities especially at the North and South Pole.

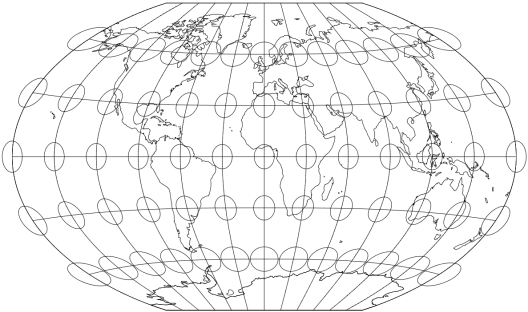
## Robinson

## 

#### Winkel Tripel

The Winkle Tripel map projection is another good minimum error map projection choice when you want to map the entire world. Some consider this to be the best compromise map projection yet for world projections as it does a reasonably good job of minimizing distortion across the entire globe without any one area being distorted significantly more than other areas.

### Winkel Tripel



### Cylindrical

Cylindrical map projections are recognized as a recommended map projection type for world projections. Cylindrical maps are popular and commonly used although these map projections are not appropriate when mapping the entire Earth.

#### Mercator

The Mercator map projection was originally developed for navigation. It is an important and useful map projection because lines of constant bearing are shown as straight lines of a map projection. The downside is there is extreme distortion at high latitudes which unfortunately has imbued a massively distorted mental map of the world in many people’s minds.

**Mercator**

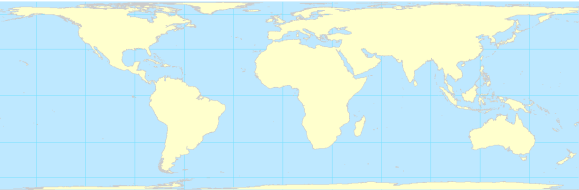


This is an illustration of the Mercator map projection, perhaps the most famous map projection of all. Note the significant distortion as you move north or south away from the equator which causes significant distortion in the northern and southern latitudes.

#### Gall-Peters

## The Gall-Peters projection was made to counteract the Mercator projection. The problem is this projection distorts third world areas thus rendering the map not useful because the shape distortion is simply too great.

**Gall-Peters**



### Map Projections Recommended for Continental Areas

There are two types of map projections that are recommended for Continental areas: Lambert Azimuthal Equal Area, and Bonne.

#### Lambert Azimuthal

The Lambert Azimuthal equal area map projection is quite versatile as the standard point can be placed anywhere. If you are mapping a hemisphere then the equatorial aspect will be your best choice. For this map projection, distortion is radial.

### Lambert Azimuthal Equal Area Map Projection

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This is the Lambert Azimuthal Equal area map projection centered over the North America region of the world.

#### Bonne

The Bonne map projection is an equal area conical projection. Scale is true at the central Meridian and each parallel. However shape distortion is severe in the northeast and northwest corners of this map projection. This map projection is best for mapping compact areas on one side of the equator.

### Bonne Map Projection

~~~~

### Map Projections for Multiple Size Countries at Mid-Latitudes

There are three types of map projections recommended for multiple size countries at mid-latitudes: Lambert Azimuthal Equal Area, Albers Equal Area Conic, and Lambert Conformal Conic.

Both the Albers Equal Area Conic and Lambert Conformal Conic map projections are great for entities that have a pronounced east-west orientation. Remember that the conic family of map projections in the normal aspect minimizes distortion of the east-west directions. Since the continental United States has a pronounced east-west orientation, the Albers Equal Area Conic map projection is great for mapping the continental United States.

In general, conic projections are adequate for mapping large entities within east-west orientation. As areas being mapped become smaller, selection of a map projection becomes less critical as the curvature of the earth is less of a factor.

**Lambert Azimuthal Equal Area**



The Lambert Azimuthal Equal Area map projection is great for groups a small countries as well as a single medium-size country. It excels at keeping distortion in check for countries of expand in all directions.

**Albers Equal Area Conic**



This is an illustration of the Albers equal area conic map projection. It is similar to the map scratch that is similar to the next map projection.

**Lambert Conformal Conic**



The Lambert Conformal Conic map projection is similar to the previous Albers equal area conic map projection and is also useful for mapping countries at mid-latitudes.

### Map Projections Recommended for Low Latitudes

There are there types of map projections that are recommended for low latitudes.

* The Lambert azimuthal equal area map projection is great for mapping low latitudes.
* A Cylindrical projection with the standard parallel at the equator is also a good choice.
* The Mercator map projection is great if the focus is on and around the equator.

## Projected Coordinate Systems

### State Plane Coordinate System

For zones within the state plane coordinate system each zone uses either the Lambert conformal conic map projection or the transverse Mercator map projection. The only exception is that Alaska uses the oblique Mercator for one of its zones. Since one of the desires of creating the state plane coordinate system was that if you work within a single zone all coordinates are in the first quadrant and positive, the y-axis false origin is typically placed 600,000 m, or 2,000,000 feet, west of the zones central Meridian.

The placement of the x- axis false origin is more arbitrary and may change from zones. You may run into a situation where the area that you are mapping crosses multiple state plane coordinate system zones. There are two common solutions to this problem. One is to use the most central zone if the zones are prominently east-west in orientation. The second option is to choose one north-south zone and adjust the central Meridian to provide a balanced look.

**State Plane Coordinate System**

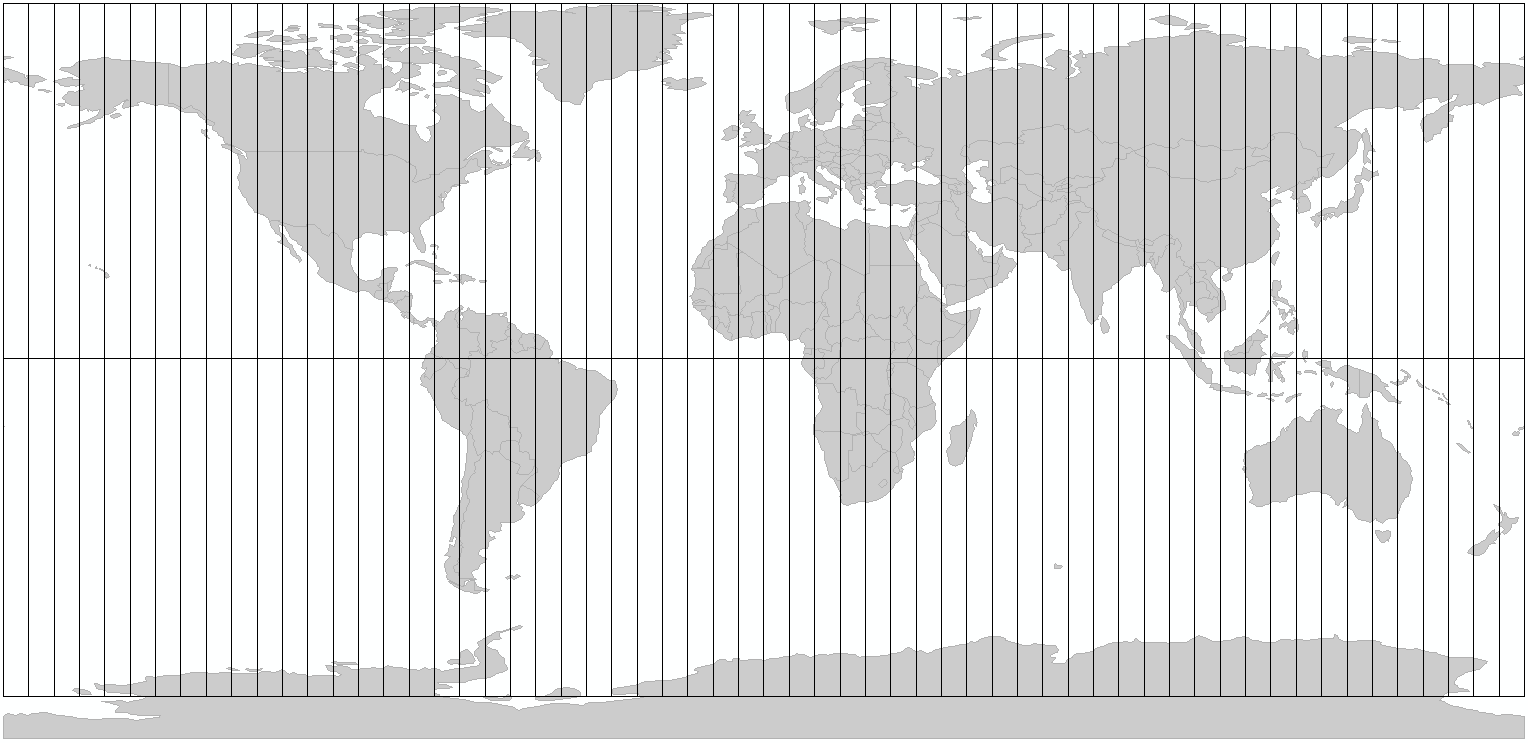


This is an illustration of all of the state plane coordinate system zones of the contiguous United States. The zones that have a predominant east-west orientation are mapped using the Lambert conformal conic map projections is that map projection minimizes distortion in the East and West directions. The zones that have a prominent north-south orientation are mapped using the transverse Mercator map projection as that map projection minimizes distortion in the North and South directions.

### Universal Transverse Mercator (UTM)

The Universal Transverse Mercator (UTM) coordinate system is generally not as accurate as a state plane coordinate system. This coordinate system uses the transverse Mercator projection with the central Meridian running through the center of each zone. The y-axis false origin is placed 500,000 m west of the zone central Meridian. The x-axis false origin for each zone is at the equator for North Hemisphere and 10,000,000 m south of the equator for the southern hemisphere.

**Universal Transverse Mercator Coordinate System**



This is an illustration showing the universal transverse Mercator map projection. There are 60 zones that start at zone one which is at -180° longitude and heads East 360° around the earth. The zones are split into North and South about the equator.

### Map Projection Reference Websites

Here are three recommended map projection reference websites.

[USGS Map Projections Poster](http://egsc.usgs.gov/isb/pubs/MapProjections/projections.html)

The USGS map projections poster provides illustrations and information about many common map projections, and useful matrices to show when the use of a particular map projection is appropriate.

[Radical Cartography Projection Reference](http://www.radicalcartography.net/?projectionref)

The radical cartography projection reference also shows helpful illustrations, and information about when to use certain map projections.

[Flex Projector](http://www.flexprojector.com/)

Flex projector is a free piece of software that allows you to create your own map projections, and export them into projection files for use elsewhere.

## SUMMARY

This lesson provided examples and information about Geodesy and Coordinate Systems. The lesson identified the determining factors one should consider when creating map projections, deformation and distribution of the projection, and how to determine which map projection to use for a project.

## ASSIGNMENTS

1. Quiz: Geographic Referencing Systems and Map Projections

2. Lab: Exploring Coordinate Systems and Map Projections