

## Week 3 - Geodesy and Coordinate Systems

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### Introduction

In this lab, you will explore the effects of various map projections on the characteristics of a map using ArcMap 10.1. ArcMap 10.1 is part of the ArcGIS Desktop 10.1 suite of programs and is used to visualize, query, and analyze spatial information.

This lab will focus primarily on shape and area distortions and will examine projections useful for mapping on the global scale as well as on the national and state level.

This lab includes the following tasks:

1. Setting Map Projections and Coordinate Systems in ArcMap 10.1
2. Exploring World Map Projections
3. Exploring National Map Projections
4. Exploring State Map Projections

### Objective: Explore and Understand Map Projections and Coordinate Systems

The map projection is a fundamental part of the mapping process, which provides the backbone, or framework, for the map. For the cartographer, selection of an appropriate map projection is a crucial part of the map design process. It is important for the map designer to understand the qualities of the mapped region that will be preserved by a given projection and the qualities that will be distorted or skewed.

The transformation of the ellipsoid shape of the earth to a two-dimensional surface cannot be accomplished without some element of distortion, through shearing, tearing, or compression. For mapping small Earth areas (large scale mapping), projection is not a major issue, but as the scale becomes smaller, as in the mapping of continents or subcontinents, distortion becomes a significant factor. Distortion of area, shape, distance, and direction become properties to consider. It is impossible for one projection to maintain all of these properties simultaneously.

Projections can be classified according to the properties they preserve. Equal-area (or equivalent) maps, for example, preserve areal relationships, but tend to lose conformality (preservation of shape). Conformal projections, on the other hand,

maintain shape over small areas but produce areal distortion. In thematic mapping, it is frequently more important to maintain correct area properties, since area is often an important element of what is being shown by the map. Therefore, shape is at times compromised through the choice of an equivalent projection. In fact, for most small-scale maps, conformality cannot be maintained over the entire area; rather, the projection may preserve shape best along a standard line, with shape distortion increasing with distance from the line. Another property to consider is distance preservation (equidistance), which preserves distance measurements along great circle arcs. Finally, direction preservation (azimuthality) maintains correct direction from one central point to all other points.

There are hundreds of possible projections from which to choose. Some distort less in certain ways than others. It is up to the map designer to select the projection that produces the least amount of unwanted distortion. Many computer mapping software packages now allow the cartographer to easily switch between various projections, making it easy to choose the one most appropriate.

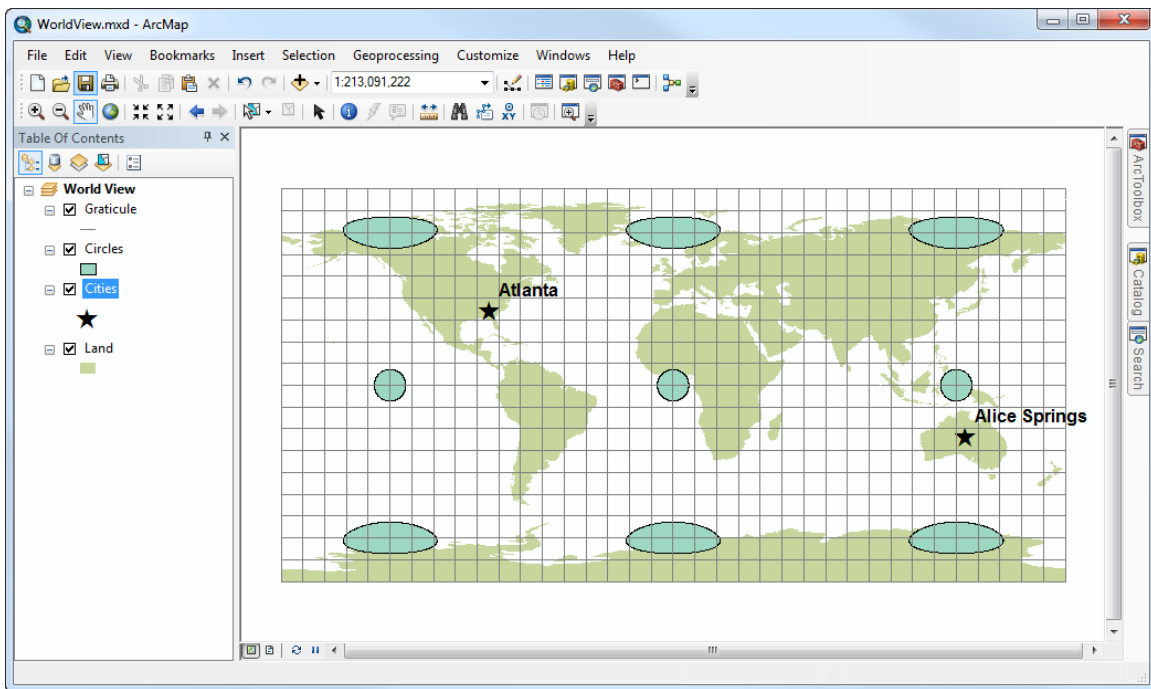
In the selection of a projection, several key elements must be considered:

- **Projection properties** - Are the properties of the projection suitable to the map's purpose? Considering the properties of shape, distance, direction, and area, which ones must be preserved, and which can be sacrificed? Or is compromise of all four the best choice?
- **Deformational patterns** - Is the amount of deformation acceptable?
- **Projection center** - Can the projection be centered easily on the area being mapped?
- **Familiarity** - Is the appearance of the map recognizable to the map reader or will it detract from the map's purpose?

## 1 - Setting Map Projections and Coordinate Systems in ArcMap

In this task, you will explore the effects of various projections on the characteristics of a map. We will focus primarily on shape and area distortions. We will examine projections useful for mapping on the global scale.

1. The data for this lab is located at: `\\socc.edu\Public\Departments\GIS\GEOG275 - Fundamentals of Cartography\Week 3\Lab Data`. Copy this data to a new working directory of your choosing on the local hard drive or removable backup.
2. Start ArcMap.
3. In ArcMap, open the project, **WorldView.mxd** by clicking **File->Open**. You should see the map shown below.



WorldView.mxd is a *map document*. A map document contains information about a map such as: list of layers, coordinate system, symbols, labels, custom tools, map elements, and much more.

In the map document, there are two polygon themes, Circles and Land, a point theme, Cities, and a line theme, Graticule. On this map, a projection has not been chosen in ArcMap. The software is using latitude and longitude measured in geodetic decimal degrees, which displays a simple rectangular coordinate system in which the length of one degree of longitude is consistently equal to one degree of latitude. In ArcMap, when a projection has not yet been selected, distance calculations remain true, since the software computes distance using the *spherical* coordinates of latitude and

longitude along a great circle arc, just as if you were actually measuring at the Earth's surface. Although a projection has not yet been chosen by the user, the display is essentially a Plate Carree projection. On a projection that preserves shape, the polygons on the Circles theme appear as true circles. In a Plate Carree projection, linear scale, area, and shape are all distorted increasingly toward the poles as demonstrated with the Circles theme.

The Circles theme will be used in this exercise for illustrating the areal and shape distortion that occurs with various projections. While this method does not actually quantify the distortion, as does Tissot's indicatrix, it does show visually the skewing, tearing, and shearing that occur with certain projections.


First, we'll examine the map units and distance units set for this "unprojected" map.

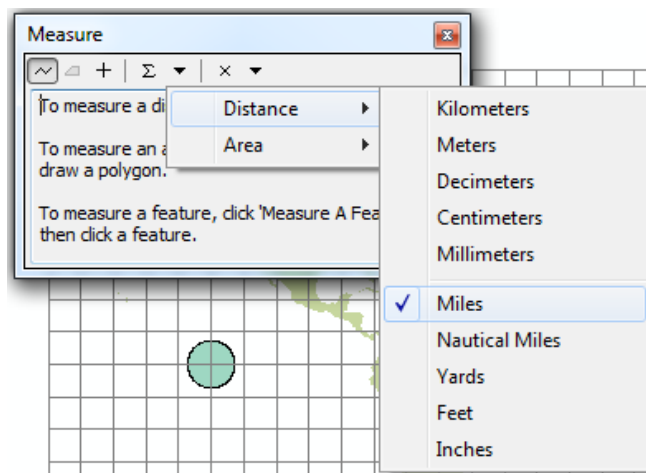
4. From the menu bar, select **View->Data Frame Properties**.

In the Data Frame Properties dialog box, notice the Map Units are set in decimal degrees and the Display Units are set in miles. This means the coordinates that are being mapped (in this case the boundaries of the land areas, the graticule, and the locations of the two cities) are stored in decimal degrees, and the measuring units are in miles.

5. Click on the **Coordinate System tab**. Notice that the current coordinate system is not known.
6. Click **Cancel** to close the Data Frame Properties dialog box.

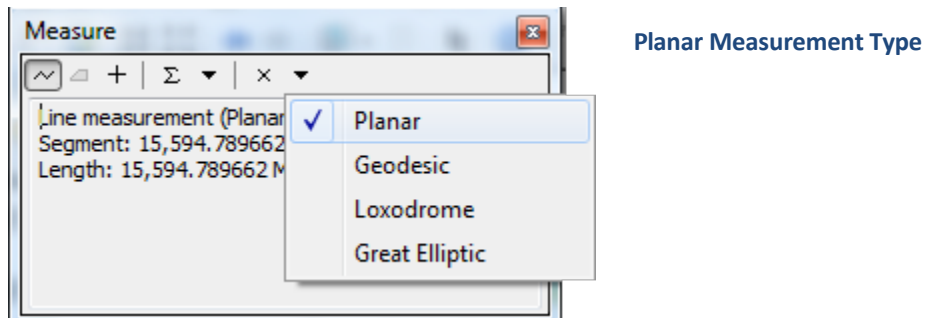
Now we'll do some distance measurements on this map for later comparison to maps in which a projection is set.

7. Click on the **Measure** tool,  , on the standard toolbar. The Measure box will appear.
8. Click the **Choose Units** dropdown and select **Distance->Miles**.



**Miles Distance Selection**

10. Click the **Measurement Type** dropdown and select **Planar** as shown in the figure below.



11. Click on the location star symbol for Atlanta, in the United States.

12. Move the cursor to the location star symbol for Alice Springs, Australia, then double-click to end the line. The distance between Atlanta and Alice Springs will be displayed in miles in the Measure box.

The *measured* distance is about 15,500 miles (your distance may vary slightly). ***This is not the actual distance between Atlanta and Alice Springs.*** Since the coordinate system is undefined in the Data Frame Properties, ArcMap measures directly between Atlanta and Alice Springs (along your measure line) heading East from Atlanta. What it *should* do is measure to Alice Springs by heading west from Atlanta instead of east as you defined since heading east is a shorter distance than heading west. However, ArcMap does not know that the “World is round” so-to-speak, since it does not know that it is working with a World-based coordinate system. This view *does not* maintain spherical distance measurements, and distorts shape, direction and area.

Tell ArcMap that you are, in fact, working with a World-based coordinate system.

13. From the menu bar, select **View->Data Frame Properties.**

14. Click on the **Coordinate System tab.** Select the **WGS 1984** coordinate system by expanding the following folders: **Geographic Coordinate Systems->World.**

15. Click the **General Tab.** Set the **Display Units to Miles.**

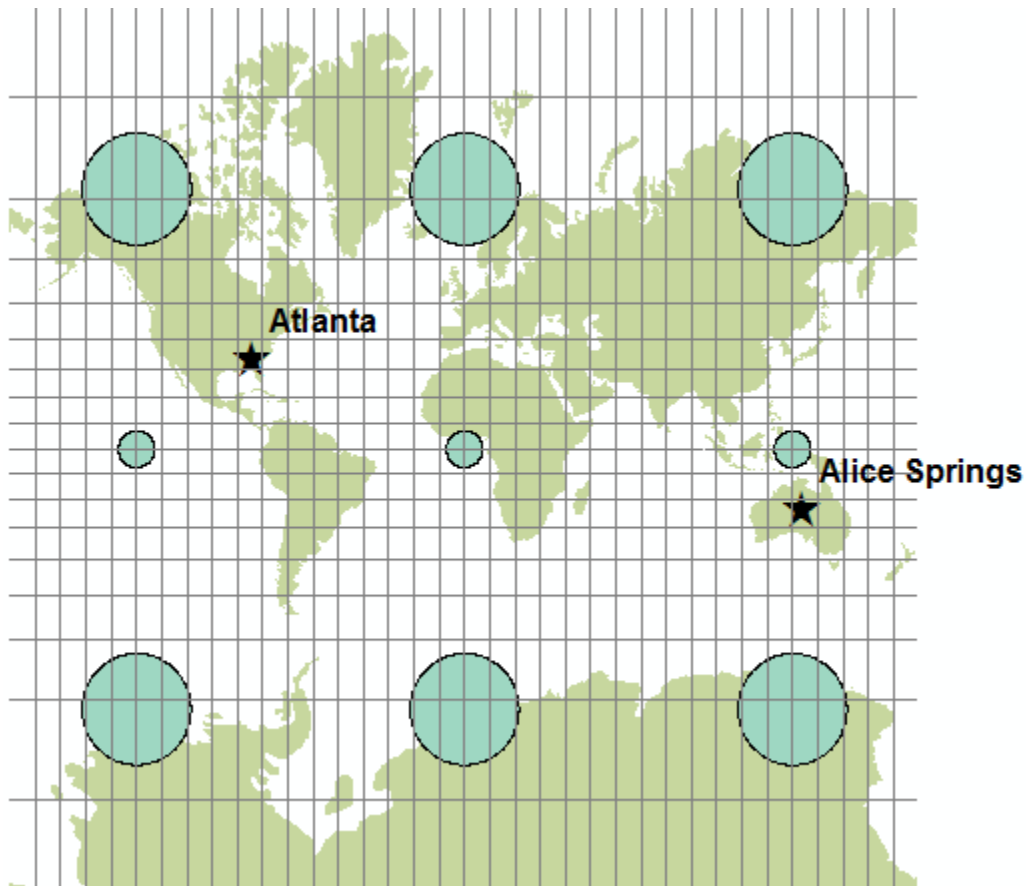
16. Click **OK** to view the map.

17. Measure the distance between Atlanta and Alice Springs again.

The *measured* distance is about 10,030 miles (your distance may vary slightly). This is also the *actual* distance between Atlanta and Alice Springs. This view maintains spherical distance measurements, but distorts shape, direction, and area.

Let's change the projection on this view to the Mercator projection.

18. Open the **Data Frame Properties** again and select the **Coordinate System** tab.
19. Select the **Mercator (world)** coordinate system by expanding the following folders:  
**Projected Coordinate Systems->World.**
20. Click **Apply** to apply the coordinate system.
21. Click the **General tab** . Notice that the *map* units are in meters.
22. Click **OK** to view the map.



The Mercator projection, a conformal projection (except at the poles), has straight meridians and parallels that intersect at right angles. Scale is truest along the equator, and becomes more distorted at higher latitudes, as evidenced by the increasing size of the circles. The Mercator was designed for marine navigation and gives all straight lines on the map as lines of constant compass bearing. For global scale thematic maps, however, the Mercator has too much areal distortion for accurate use. Let's see how the Mercator handles distance measurement.

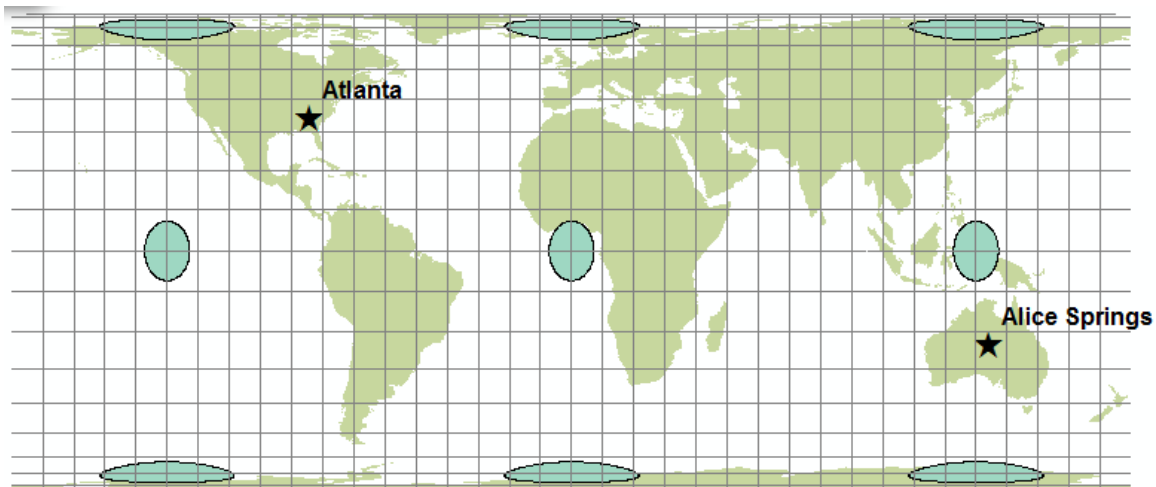
23. Measure the distance between Atlanta and Alice Springs again using the measure tool.

The new measurement is about 15,647 miles, much more than the true distance (your measurements will likely vary somewhat.) The Mercator is best for larger-scale projections of areas at low latitude. Small-scale maps have much distortion of area and distance.

Now let's examine the Behrmann projection.

24. In **Data Frame Properties**, select the **Behrmann (world)** coordinate system by expanding the following folders: **Projected Coordinate Systems->World**.

25. Click **OK** to view the map. You should see the map shown in the figure below.



The standard parallels are at 30 degrees North and South, so the least areal distortion will occur in these locations.

The Behrmann Projection is a cylindrical equal-area projection that, as opposed to the Mercator, de-emphasizes areal exaggerations in the higher latitudes. This projection was adopted by organizations concerned that the Mercator projection showed European dominance, in terms of area, over the Third World. It does preserve area, but there is shape distortion. The greatest shape distortion occurs along the equator and at the poles. Equatorial continents are stretched in a north-south direction. Let's see how the distance property fares.

26. Measure the distance between Atlanta and Alice Springs again using the measure tool.

Distance between the two cities in the Behrmann projection measures approximately 13,790 miles, still greater than the true distance.

These two rectangular maps are much less desirable for mapping continents than other projections as they have significant distortion and also can promote geographical misconceptions. In general, rectangular maps are not recommended for use in mapping the world. Equivalency (the property of equal area) and conformality are better preserved using non-rectangular maps. In the next task, we will examine a map projection more suitable for mapping the world.

## 2 - Exploring World Map Projections

Let's examine a map projection more suitable for mapping the entire world: the Mollweide projection, a pseudo-cylindrical projection. First, let's create another view in ArcMap so that we can compare the Mollweide projection to other map projections side-by-side.

1. From the menu bar, click **Insert->Data Frame**. A new data frame will appear in the Table of Contents.
2. **Select all of the layers from the *World View* data frame** by holding down the *Ctrl* key on your keyboard while clicking on each of the four layers.
3. **Right-click on one of the selected layers**, then choose **Copy**.
4. **Right-click on the new data frame**, then choose **Paste Layer(s)**. The layer will be copied to the new data frame and the map will appear.

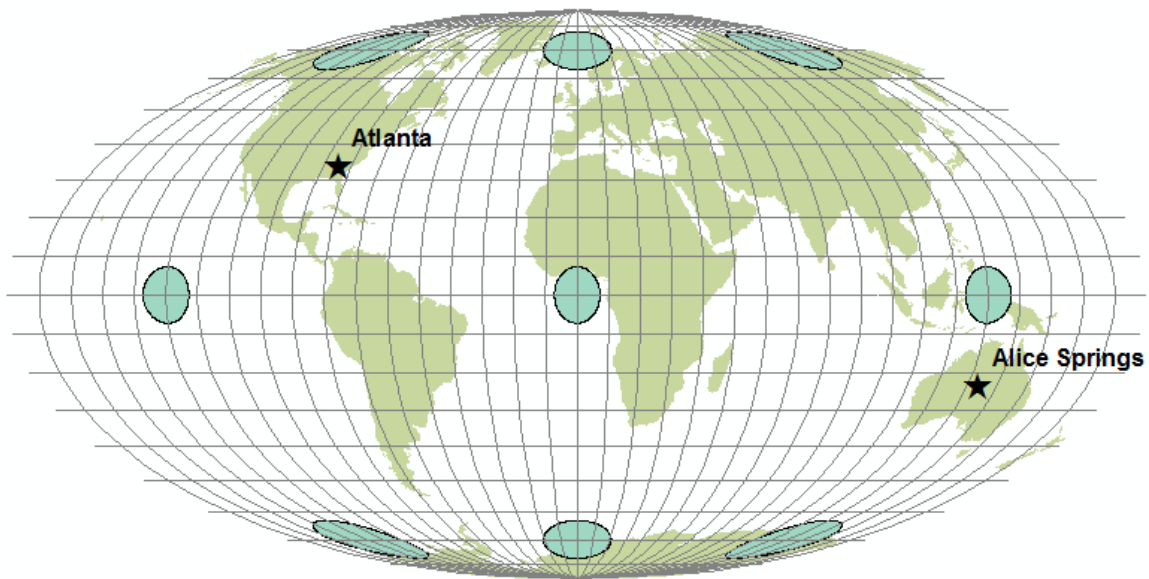
A data frame is a collection of layers that, together, compose a map view. A map document (.mxd) can contain multiple data frames, each containing the same, or different data layers. To switch back and forth between data frames, right-click on the data frame you wish to see, then click *Activate*. The data frame's label will become bold and you will see that map.

Let's now select the Mollweide projection in the new data frame.

5. With the new data frame activated, from the menu bar, select **View->Data Frame Properties**. The data frame properties only display properties for the activated data frame, which, in this case, is the new data frame that we just created.
6. Click on the **General tab**. We will provide the new data frame with a descriptive name for easy reference.
7. In the **Name** field, enter *Mollweide Map Projection*.
8. Click on the **Coordinate System tab**. Select the **Mollweide (world)** coordinate system by expanding the following folders: **Projected Coordinate Systems->World**.
9. Click **OK** to view the map.

The Mollweide is commonly used for world maps as it is equal-area and minimizes shape distortion, resulting in a map that is pleasing to the eye. Its central meridian, in this case the prime meridian, is straight, with other meridians curved. (Note: to specify a central meridian other than the Prime Meridian, double-click on Mollweide (world) in the Data Frame Properties Coordinate System dialog box, then enter a new value for Central Meridian) The parallels are all horizontal and straight. The linear scale is true along the parallels at 40° 30' North and South.





Let's see how the distance property fares.

10. Using the **Measure** tool, measure the distance from Atlanta to Alice Springs.

The distance measures approximately 13,311 miles (you may need to change the units to miles if they are set to something different). The Mollweide is therefore not an equidistant projection.

Let's save our work so we can reference it later.

11. From the menu bar, click **File->Save As...** Name your map document and save it to your working directory.

### 3 - Exploring National Map Projections

Projections suitable for mapping the world are not necessarily the best for mapping smaller areas, such as continents or countries. When mapping at such a scale in the mid-latitudes, it is important to use a projection that is centered on the area being mapped and has a standard line, or lines, passing through the area being mapped.

In this task, we'll look at a map of the contiguous United States using a few different projections.

1. In ArcMap, open the project, **CountryView.mxd** by clicking **File->Open**.

CountryView.mxd is an "unprojected" map of the lower 48 states comprised of three themes: United States, LA & NYC, and Circle (centered on -97.50, 39.00). You can see it does not look quite right given the default Geographic (Plate Carree) projection. The circle shows some obvious skewing.

The distance property is more difficult to judge. The known distance between Los Angeles and New York is approximately 2,451 miles. Let's see how the "unprojected" map controls distance distortion.

2. Use the **Measure** tool as before to measure the distance between Los Angeles and New York City in miles.

The distance in the "unprojected" view returns an answer 44.66 unknown units! ArcMap is unable to determine what units the data is using. The data is using the WGS 1984 coordinate system, which uses decimal degrees to report locations. We will now set the map units as decimal degrees to see if ArcMap will measure the distance between the two cities for us in miles.

3. In the **Data Frame Properties**, on the **General** tab, set the **Map Units** to **Decimal Degrees**. Click **OK** to set the changes.
4. Use the **Measure** tool to measure the distance between Los Angeles and New York City in miles using the **Geodesic** measurement type. We are measuring using the Geodesic measurement type because the coordinate system of the data layers (WGS 1984) is a worldwide coordinate 3D coordinate system that takes the curvature of the Earth into account. When measuring between LA and NY, click on one city and then click on the other city and move your cursor away from the final point to view the distance.

The measurement will now be virtually the same as the actual distance of 2,451 miles. Remember, for this projection in ArcMap, coordinates are treated as spherical latitude and longitude. Distance is calculated as if along a great circle arc and so the actual ground distance is preserved. Shape and areal properties, however, are distorted.

Now we will project the data using the Mollweide projection. The Mollweide did a nice job with the whole world, but we'll see how it fares with a single mid-latitude country.

5. Open the **Data Frame Properties** and set the map projection to **Mollweide (world)**.  
You may need to zoom to full extent to view the map.

There clearly is a great deal of distortion using this projection, most obviously the shearing. Part of the problem lies in the fact that this projection is centered at 0 degrees longitude. Let's center the projection on the United States.

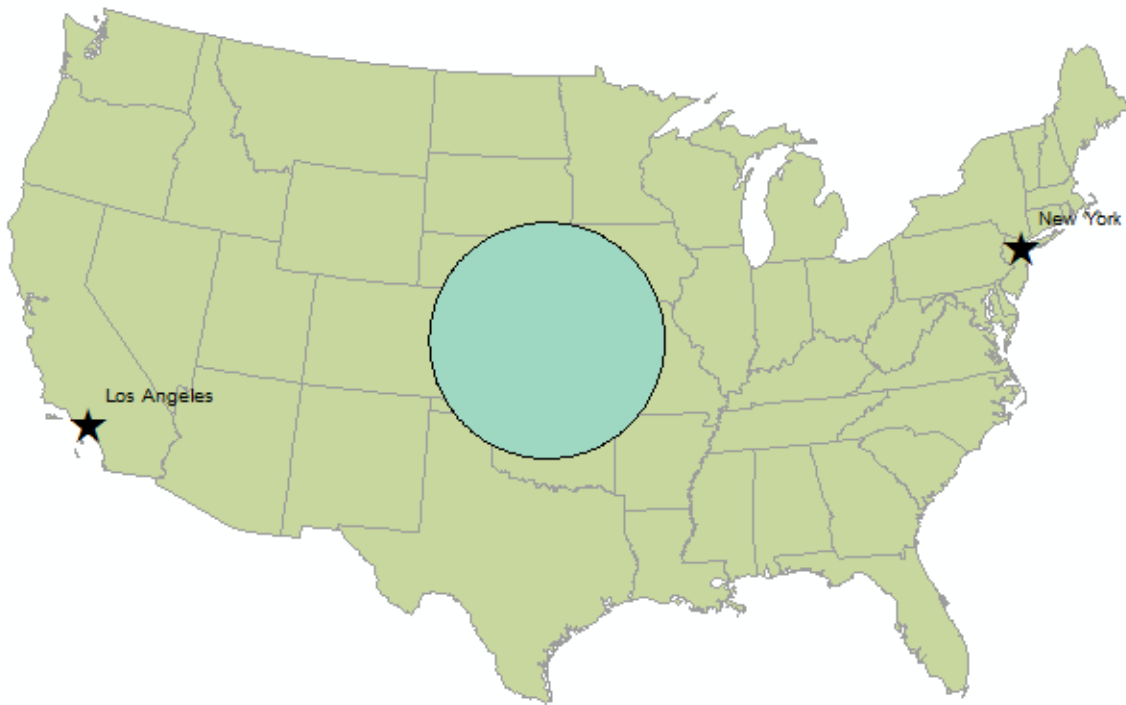
6. Open the **Data Frame Properties**, then click on the **Coordinate System tab**.
7. Find the current map projection, Mollweide (world), and **right-click on Mollweide(world) then choose Copy and Modify...**
8. Change the name of the projection to **USA\_Mollweide**.
9. Change the central meridian so that the projection is centered at -96.000 degrees longitude instead of 0.000. This will center the projection down the middle of the country.
10. Click **OK**, then **OK**.

This is a distinct improvement in shape, but there is still some skewing. The Mollweide projection is primarily used for mapping the entire world. For mapping large countries, at mid-latitudes, such as the United States, other projections are more appropriate.

The Lambert azimuthal, Albers equal-area, Bonne equal-area, and Lambert conformal conic projections are examples of suitable projections for mapping the entire U.S.

Because it has two standard parallels, the Albers equal-area projection is particularly good for larger countries with a significant east-west extent. Let's try Albers on our map.

11. Once again, open the **Data Frame Properties** and click on the **Coordinate System tab**.
12. Select the **USA Contiguous Albers Equal Area Conic** coordinate system by expanding the following folders: **Projected Coordinate Systems -> Continental -> North America**.
13. You will get a coordinate system warning, click **Yes** to dismiss it.



The Albers conic projection has low-scale distortion for an area the size of the U.S. As the area being mapped decreases in size, distortion is less of an issue.

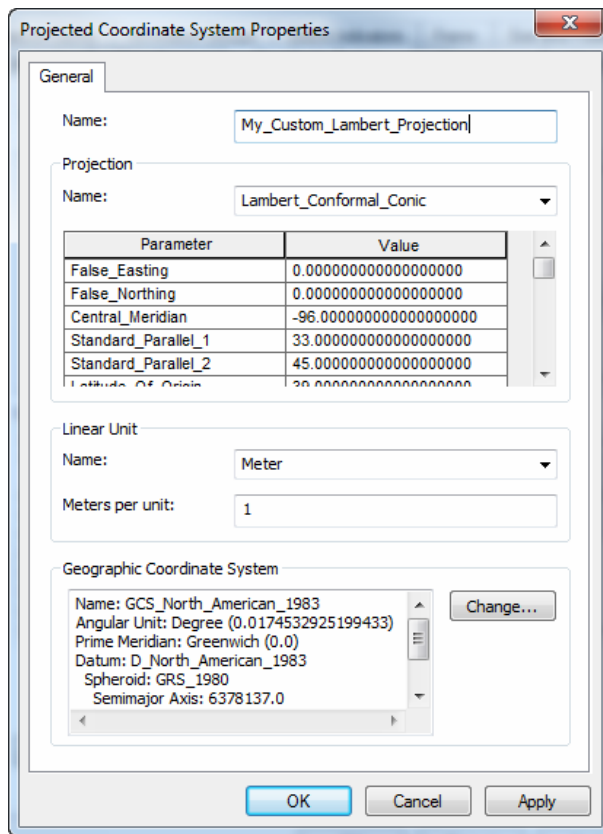
14. Click on the **Measure** tool again and measure the distance between Los Angeles and New York City. It should be about 2,428 miles, still about 23 miles short.

Let's try another map projection to see what changes.

15. Open the **Data Frame Properties** and click on the **Coordinate System tab**.
16. Expand the following folders: **Projected Coordinate Systems -> Continental -> North America**.

Under ArcMap's standard options for the Projections of the Continental North America category, you will also find the USA Contiguous Lambert Conformal Conic and the USA Contiguous Equidistant Conic. Both of these standardized projections have two standard parallels and are centered at -96.000 degrees longitude, the same as the Albers projection. Let's examine the custom options so we can modify the map projection to our needs.

17. Find the map projection **USA Contiguous Lambert Conformal Conic**, and right-click on the projection then choose **Copy and Modify...** This will once again open the **Projected Coordinate Systems Properties** dialog (shown below).



There are many choices under the Custom option of the Projection Properties window. You can customize one of the projection selections so that it is centered on the area in question, in this case the United States, simply by redefining the particular cartographic settings, such as the central meridians, standard parallel(s), reference latitude, or false eastings and northings. The choice of parameters varies depending on which projection is being used. Let's briefly define these terms.

- ❑ **False easting** - in ArcMap, the x-coordinate value for the x-origin. For example, if the central meridian for your projected map is -96.00, and the false easting is set to 0.00, then all locations along that meridian are assigned a value of 0.00. All locations to the west of the central meridian (x-origin) are assigned a negative value, and all locations to the east of the central meridian are assigned a positive value, as in a typical Cartesian plane.

- ❑ **False northing** - in ArcMap, the y-coordinate value for the y-origin. For example, if the reference latitude for a conic projection is 37.00, then all locations along that parallel are assigned a value of 0.00. All locations to the south of the reference latitude (y-origin) are assigned a negative value, and all locations to the north of the reference latitude are assigned a positive value, as in a typical Cartesian plane.
- ❑ **Central meridian** - the longitude on which a map is centered (x-origin).
- ❑ **Standard parallel(s)** - the latitude on which a map is centered (sometimes the y- origin), or for conic projections, the parallels along which the cone touches the earth.
- ❑ **Latitude of Origin** - the latitude on which a map is centered (y-origin).

For now, we'll leave the default settings for the central meridian, latitude of origin, standard parallels, and false easting and northing. In setting map projections, the choice of spheroid, or reference ellipsoid, is also an important consideration. In this example, the spheroid is currently set to GRS\_1980.

- ❑ **Spheroid** - a model of the earth's shape used in transforming a projection. The reference spheroid, or ellipsoid, is generated by choosing the lengths of the major and minor axes that best fit those of the real earth. Many such models are appropriate for different locations on the earth.

Closely related to the concept of the spheroid is the concept of the datum. The North American Datum of 1927 (NAD27) uses the Clarke 1866 reference ellipsoid, whereas the North American Datum of 1983 (NAD83) uses the Geodetic Reference System (GRS) 1980 reference ellipsoid.

- ❑ **Datum** - selecting and orienting a specific spheroid to use for a location. Let's

continue selecting our projection parameters.

18. Set the **Linear Unit** to **Mile\_US**. Remember, these units are displayed in the information bar on the bottom right of the screen. Map Units are used to express x and y coordinates. We'll be examining, using miles, the effect on the x and y coordinates of setting the false easting and northing to 0.00. (Note: ArcMap only allows x and y coordinates to be expressed in decimal degrees in "unprojected" or "geographic" projections. Decimal degrees are not an option for the Lambert Conformal Conic projection in ArcMap.)

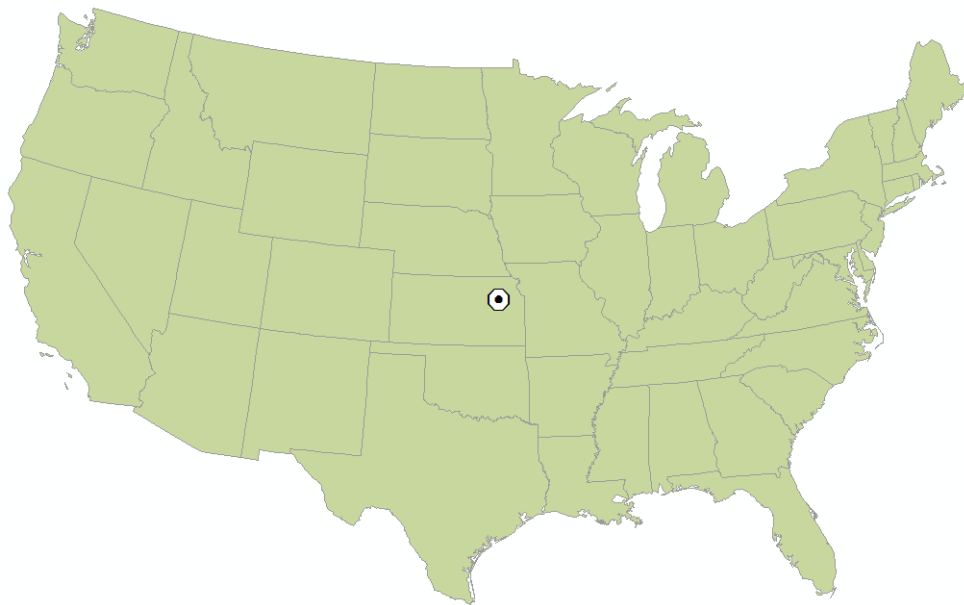
19. Click **OK**.

Now let's see the effect of the 0.00 settings for the false easting and northing. The x- origin is approximately -95.85 and the y-origin is approximately 37.16.

20. In the Table of Contents, **turn off the Circle layer** to see southeastern Kansas, the location where the x and y origins intersect.

21. Turn on the **Intersection Point layer** to see where the x and y origins intersect.

In the figure below, a white octagon with a centered, black dot illustrates the intersection of the x and y origins. At this intersection in the view, the x and y coordinates are 0.00, 0.00. As you move to the northeast, both the x and y coordinates are positive. The values of the x and y coordinates are expressed in miles from the origin. As you move to the southwest of the intersection, the x and y coordinates are both negative. Experiment with the changing coordinate values and other projections on your own.



**Intersection of X and Y Origins**

The conic projections function quite well for mapping the larger states in the U.S. In terms of thematic mapping, it is important that maps at this scale are equal-area. Any other properties important to the particular map should also be considered when selecting a proper projection. We will now examine projections and grid systems for large scale maps, such as for small states, counties, or local regions.

## 4 - Exploring State Map Projections

The State Plane Coordinate System (SPCS) was developed to provide a simple rectangular coordinate system for large scale mapping use (i.e. small areas of the earth), such as surveying and engineering projects. ArcMap Help states:

*“The SPCS is not a projection. It is a coordinate system that divides all fifty of the United States, Puerto Rico and the US Virgin Islands into over 120 numbered sections, referred to as zones. Depending on its size, each state is represented by anywhere from one to ten zones. The shape of the zone then determines which projection is most suitable. Three projections are used: the Lambert Conformal Conic for zones running east and west, the Transverse Mercator for zones running north and south, and the Oblique Mercator for one zone only, the panhandle of Alaska. Each zone has an assigned USGS code number, each having a designated central origin, which is specified in degrees.”*

The original state plane system, developed in the 1930s, was based on the North American Datum of 1927, with coordinates measured in feet. Today the state plane system is based on the North American Datum of 1983, and coordinates are in meters.

The coordinate grids cover small areas with minimal areal or distance distortion. For small states, one grid is sufficient, while for larger states, more are required to cover the entire area. Alaska, for example, needs ten grids. The state plane system, therefore, is only appropriate for mapping small Earth areas, such as the smallest states, city grids, or local regions. The smallest states, which only have one state plane zone, can be represented in their entirety using the SPCS.

Let's create a map display of Vermont, using the State Plane Coordinate System. Vermont is one of the smaller states. It has only one state plane zone.

1. In ArcMap, open the project, **Vermont.mxd** by clicking **File->Open**.
2. From the menu bar, select **View**, then **Data Frame Properties**.
3. Click on the **Coordinate System** tab. Select the **NAD 27 StatePlane Vermont FIPS 3400** coordinate system by expanding the following folders: **Projected Coordinate Systems | State Plane | NAD 1927 (US Feet)**.

Note that the projection used is Transverse Mercator and the spheroid is Clarke 1866. The central meridian is -72.5, which runs through the center of the state. The reference latitude, or y-origin, is 42.5, which is just south of Vermont. The false easting is set to 152,400.30480 meters, or its equivalent, which is 500,000 feet. The false northing is set to 0.00. So, the false origin will be to the west (500,000 feet west of -72.5) and south (42.5) of the state of Vermont.

4. Click the **General** tab.
5. **Set the Display Units to Feet.**



6. Click **OK**. Click **Yes** to dismiss the warning. If you no longer see Vermont, right-click on the Vermont layer in the Table of Contents then click **Zoom to Layer**.

Scroll around the state and notice the changing coordinates. If you have a USGS topographic map of any part of Vermont, based on NAD27, the coordinates displayed here will match the SPCS coordinates shown on the hardcopy map. Try mapping other states using the State Plane Coordinate System. Keep in mind that most states are comprised of more than one SPCS zone. Although an entire state will display if you select one of these zones, *only the area that is actually a part of this zone will be projected serviceably.*

The Universal Transverse Mercator (UTM) grid is a plane coordinate system that spans almost the entire globe. It is probably the best known plane coordinate system of international scope. For the UTM system, the globe is divided into sixty zones, each comprised of six degrees of longitude. Each zone has its own central meridian. The limits of each zone are 84 degrees north and 80 degrees south. UTM uses the Transverse Mercator projection. Experiment with the UTM system using both the United States and the world.

Some final notes on projections:

When you import spatial data into ArcMap, you must know the projection (if any), the grid system, and the datum, of your data. Mostly you will find the data in decimal degrees, that is, latitude and longitude coordinates. Base maps with underlying coordinates that are geodetic decimal degrees are the most versatile when constructing a map database. This data can be worked with as an “unprojected” map, or you can designate a preferred projection. If the data are already projected, you will need to go to the Data Frame Properties | Coordinate Systems dialog box and specify the units in which the data are stored. Then you will be able to accurately perform analysis and measurements using the map.

## Conclusion

In this lab, you have explored coordinate systems and map projections. Each map projection distorts the Earth differently. You are able to modify the map projections provided in ArcMap 10.1 to suite your mapping needs. It is important that you set the correct map projection for each data layer, and for the data frame.

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