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Unit 10: Projecting Data

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The NCGIA GIS Core Curriculum for Technical Programs

UNIT 10: PROJECTING DATA

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Context

A map projection defines the manner in which three-dimensional information about the Earth is transformed to a two-dimensional surface for display and analysis. All spatial data stored in a GIS are associated with a map projection, either implicitly (so-called "unprojected" data stored with raw longitude, latitude coordinates) or explicitly (where the data have been transformed into a known map projection). Map projections are a particularly important feature of spatial data because they introduce error and distortion, since a sphere cannot be transformed to a plane without some stretching and twisting of the sphere's surface.

The typical GIS package supports anywhere from 5 to 50 map projection types, and most projections may be modified or customized by varying their parameters. This flexibility is important for two reasons: first, in order to use two or more layers together in a GIS for visualization or analysis, all data must be projected in the same way. Second, certain types of analyses, such as the measurement of area, are only valid when using certain types of projections (and conversely, are completely wrong when using an inappropriate projection).

An understanding of map projections is essential in order to confidently display, analyze, and interpret GIS data. The subject of map projections is vast and complex. This unit attempts to present an overview of projection issues that are likely to be encountered by a GIS user.

Example Application

As GIS analyst on a large ecological modeling project in the Pacific Northwest, you are constantly on the lookout for higher-quality data with which to upgrade your environmental database. On the World Wide Web you discover a new set of Digital Elevation Model (DEM) data: the GTOPO30 Database from the US Geological Survey, which provides high-quality elevation data over the entire globe at a 30-arc- second grid resolution.

You decide to upgrade your existing DEM data with the newer, more extensive, and more carefully documented GTOPO30 data, however your current environmental database is on an Albers equal-area conic map projection, while GTOPO30 uses a Plate Carree projection and a simple longitude, latitude coordinate system.

In order to use the new data with your existing environmental database, you will need to project it from Plate Carree to Albers equal-area conic, making appropriate decisions regarding the grid resolution and the resampling method.

Learning Outcomes

The following list describes the expected skills which students should master for each level of training, i.e. Awareness/Competency/Mastery.

Awareness:

Students should be able to discuss the issues of map projection and map distortion as they relate to GIS; and to demonstrate a working knowledge of some common map projections and associated parameters.

Competency:

Students should be able to project spatial datasets into a new map projection; to identify appropriate (and inappropriate) projections for certain GIS applications; and to create a custom map projection.

Mastery:

Students should understand the issues involved with projecting raster data, including the choice of grid cell size and resampling methods.

Preparatory Units

Recommended:

- (UNIT 7) - Using and interpreting metadata
- (UNIT 9) - Converting spatial data between formats, systems, and software
- (UNIT 24) - Collecting GPS data

Complementary:

- (UNIT 8) - Error checking
- (UNIT 11) - Registration and Conflation
- (UNIT 12) - Planning a digitizing project
- (UNIT 16) - Planning a scanning project
- (UNIT 36 - Using distance and connectivity operators

Awareness

Learning Objectives:

The student will be able to:

1. Define "map projection" and the basic classes of map projections
2. Discuss the types of distortion inherent in map projections
3. Demonstrate familiarity with some commonly-used map projections and coordinate systems
4. Discuss the required parameters for several common map projections

Vocabulary:

- Map Projection
- Coordinate System
- Latitude, Longitude
- Parallel, Meridian
- Great Circle
- Rhumb Line, Loxodrome
- Geoid
- Ellipsoid, Spheroid
  - Clarke 1866
  - WGS80
- Datum
  - NAD27
  - NAD83
- Equal-Area
- Conformal
- Equidistant
- Azimuthal
- Transverse
- Oblique
- Tangent, Secant
- Distortion
  - Area Distortion
  - Shape Distortion
  - Distance Distortion
  - Direction Distortion
- Scale Factor
- Standard Line

Awareness Knowledge/Skills:

- Define map projection

- A map projection is a method for transforming all or part of the Earth's spherical surface to a plane. It is impossible to transform a sphere to a plane without distorting the geometric relationships of the original data. Map projection distortion can affect the following qualities of mapped regions: shapes, areas, distances, and directions (also called bearings or azimuths).

- Certain map projections are designed to minimize a particular type or types of distortion, however no map is completely distortion-free.

Classifications of map projections

Projections can be classified by the geometric property that they preserve. Note that some map projections, because they attempt to minimize more than one type of distortion, do not fall under any of the following classes.

- **Conformal** - local shapes are preserved. Conformal maps are well-suited for navigation. Commonly-used conformal projections are the Lambert conformal conic, the transverse Mercator, and the Mercator.

- **Equal-area** - areas are preserved. Equal-area maps are well- suited for general thematic mapping. Some common equal-area projections are the Albers equal-area conic, the Lambert azimuthal equal-area, and the Mollweide.

- **Equidistant** - distances from all locations to one or two points are preserved. Equidistant maps are useful for measuring distances from fixed locations. The most common are the azimuthal equidistant, where distances from the projection center are true, and the two-point equidistant, where distances from two central points are true.

- **Azimuthal** - directions from all locations to one or two points are preserved. Azimuthal projections are well-suited for mapping polar regions, and for achieving certain special characteristics. For example, the gnomonic projection has the property that great-circle paths between any two points appear on the map as straight lines. Other examples include the stereographic, which is also conformal; and the Lambert azimuthal equal-area, which is also equal-area.

- Another general classification of map projections is the type of geometric surface to which the sphere is projected. The main projection surfaces are the cylinder, cone, and plane. Conceptually, the Earth is placed inside or adjacent to the projection surface, locations are mathematically transformed from the global coordinate space to that of the projection surface, and the projection surface is then "unrolled" (if necessary) into a flat map sheet (a plane).
- The orientation of the projection surface with respect to the globe affects the properties of the resulting map projection. The position of the surface with respect to the poles determines whether the projection is normal, transverse, or oblique. The manner in which the surface intersects the globe (tangent or secant) determines the locations on the map where scale is true. (Figure 1).

For the normal case, where the projection is neither transverse nor oblique, map projections have the following general properties:

- **Cylindrical** - Scale is true along the Equator or along two parallels equidistant from the Equator.
- **Conic** - Scale is true along one or two standard parallels.
- **Azimuthal** - Typically, scale is true at the projection center or on a circle around the center.

Distortion

All projections contain distortion, however at very large map scales (where only a small portion of the Earth is mapped), the distortion becomes negligible and the Earth may be treated as a plane. As map scale becomes smaller, distortion becomes more significant. Map projections can have some or all of the following types of distortion:

- **Area** - relative areas of mapped regions are not correct.
- **Shape** - shapes of mapped regions are not correct.
- **Distance** - relative distances between points on the map are not correct.
- **Direction** - compass directions (also called bearings or azimuths) between points on the map are not correct.

[Figure 2 shows the extreme area distortion in the polar regions of the Mercator projection, which is conformal and not equal-area. Note the areas of Greenland and Algeria. Figure 3 shows the world on an equal-area projection, the Mollweide. Note that Algeria is actually larger than Greenland.]

Projection Parameters

When defining a projection for a given GIS dataset, the type of projection must be specified (e.g. Albers equal-area conic) along with a number of parameters which describe how the projection is implemented. These parameters define, for example, the units of measurement and the positioning of the projection surface with respect to the globe. Different projections require different types of parameters. Some commonly-occurring parameters are discussed below.

- **Units** - The unit of measure used for map coordinates. Commonly-used units are meters, feet, decimal degrees (e.g. 123.267 deg W, 44.567 deg N) and degrees, minutes, seconds (e.g. 123 deg 16 min 1.2 sec W, 44 deg 34 min 1.2 sec N). Some projections are defined for a specific set of units (e.g. meters, for the UTM system [discussed later in this document]), while most projections can be used with a variety of units.

- **Scale** - Map scale is the ratio of a distance on the map to the same distance on the Earth, for example "one inch equals one mile" or "1:63,360". Because of projection distortions, scale can never be constant everywhere on a map. Most projections have one or two lines where scale is constant. The map scale at these

locations is known as the "principal scale" or "true scale". To get a feel for the distortion present in a map projection, it is important to know where the scale is true and where it deviates from true scale.

- **Scale factor** - the ratio between the actual scale at a given location and the map's principal scale. For example, if a particular meridian of a map projection has a scale factor of 0.9996, then a distance measured along that meridian and converted to Earth distance based on the map scale would be 99.96% of the true Earth distance.

- **Standard lines** - (also "standard parallel", "standard meridian") Lines on a map where scale is true (i.e. where the scale factor is exactly 1.0). A map can have zero, one, or at most two standard lines. These lines coincide with parallels or meridians for most normal and transverse projections, but not for oblique projections. Standard lines represent locations where the globe and the projection surface intersect. Note that standard "lines" may be curved or even circular. Standard lines denote regions on a map where distortion is minimized. Distortion tends to increase with distance from a standard line.

- **Origin** - The point on a map where the map coordinates are 0,0. Most projections require that an origin be specified, usually as a longitude, latitude location. The origin is often at the center of a map, however the origin can be shifted outside of the mapped region so that all map coordinates are positive numbers.

- **False easting/northing** - A constant value added to map coordinates in order to avoid negative coordinates. For example, the UTM coordinate system uses a false easting value of 500,000 meters so that all UTM coordinates are positive numbers.

- **Ellipsoid** - (also "spheroid") A model of the Earth's shape made by rotating an ellipse about its short axis. At very small map scales where all or most of the globe is mapped (e.g. 1:5,000,000), the Earth may be assumed a sphere (Snyder, 1987, pg. 11). At larger map scales the Earth's flattening at the poles becomes noticeable, and this shape is more accurately represented by an ellipsoid. The actual shape of the earth, defined by mean sea level, is known as the geoid. Two common ellipsoids are the Clarke 1866, which is used in North America, and the GRS 1980 (Geodetic Reference System), which is an internationally-accepted reference ellipsoid. GIS software typically supports a number of ellipsoid choices.

- **Datum** - A system for anchoring an ellipsoid to known locations (surveyed control points) on the Earth. Many different datums are in use around the world. Local datums are fitted to a particular region of the Earth. The North American Datum of 1927 (NAD27) is in common use and is based on the Clarke 1866 ellipsoid. A more recent North American datum, NAD83, is based on the GRS 1980 ellipsoid. Global datums are fitted to the entire globe in order to provide consistent accuracy for long- distance, global-scale measurements. The World Geodetic System (WGS) 1984 datum, based on the GRS 1980 ellipsoid, is a

common global datum. The location of a point on the Earth can differ by up to several hundred meters when the point is referenced to different map datums.

Advanced Knowledge/Skills:

Commonly-used projections and their parameters

1. Albers equal-area conic - An equal-area map projection used for continent-sized regions of primarily east-west extent. Scale is true along one or two standard parallels, and distortion increases with distance from the standard parallel(s).

A relatively common Albers projection for the contiguous USA, often called the "U.S. Albers" [Figure 4], is defined as follows:

- Standard parallels: 29.5 and 45.5 deg. N
- Central meridian: 96.0 W
- Latitude of origin: 23.0 N

2. Universal Transverse Mercator (UTM) - A conformal coordinate system, based on the transverse Mercator projection, defined over the entire globe between latitudes 84 N and 80 S. The Earth is divided into 60 zones, 6 degrees wide, numbered from 1 at longitude 180 W, eastward to zone 60 at longitude 180 E. Meters are the standard units used with UTM. The UTM system uses a false easting of 500,000 m, and, in the southern hemisphere, a false Northing of 10,000,000 m. Thus no UTM coordinates are negative. Figure 5 shows the UTM zones of the contiguous USA.

Scale: Each UTM zone contains two standard meridians where scale is true. Along the central meridian of a zone, the scale factor is 0.9996. Along the edges of a zone the scale factor is 1.00158 at the equator. Figure 6 shows the area distortion of 7.5 arc-minute boxes (quadrangles) on a map projected to UTM Aone 10. Note how the distortion increases dramatically in areas outside of Zone 10.

Origin: In a given zone in the northern hemisphere, the intersection of the zone's central meridian and the Equator is assigned the coordinates 500,000 m East, 0 m North. In the southern hemisphere the same point has the coordinates 500,000 m East, 10,000,000 m North.

In the polar regions, where UTM is not defined, the Universal Polar Stereographic (UPS) projection system is used.

3. State plane coordinate system (SPCS) - A system of map projections defined for the United States, designed to minimize scale distortion to within one part in 10,000. Each state is divided into one to five zones. Zones trending mostly North-South use the transverse Mercator projection, and zones trending East-West use the Lambert conformal conic projection. One exception is the

diagonally-trending Alaskan panhandle, which uses an oblique Mercator projection. The standard units for the SPCS are feet.

Competency

Learning Objectives:

After completing this section you should be able to:

1. Identify an appropriate map projection for some example applications.
2. Create a custom map projection.

Tasks:

1. **Application**: A parcel delivery company with an air-freight hub in Memphis, Tennessee needs a map showing flight distances between the hub and the rest of its North American market.

   Projection: use an equidistant projection centered on the hub city, in order to show correct distances from the hub. A suitable projection for this task is the Azimuthal Equidistant.

   Memphis is located at:

   - 35 deg 6' 22" N
   - 90 deg 0' 25" W

2. **Application**: The same company in the above example has added another hub in Mexico City.

   Projection: the Two Point Equidistant, a projection which presents true distance from any point on the map to either of two central points.

   Mexico City is at:

   - 19 deg 29' 20" N
   - 99 deg 3' 14" W

Mastery

Learning Objectives:

After completing this section you should be able to:

- Discuss the common resampling methods used when projecting raster data
- Project raster data, using an appropriate choice of grid resolution and resampling method

Tasks:

Projecting raster data

Raster, or gridded, datasets introduce additional issues which the GIS analyst must understand in order to properly execute map projection tasks. In general, vector data may be converted from projection A to projection B, and then back to projection A with essentially no loss of information (except for rounding and machine precision). This is because vector-based locations (points and vertices), can be unambiguously located in the coordinate system of a map projection. A raster, on the other hand, is constrained by the fact that it must reference a grid of equally-spaced grid cells. In addition, while a vector-based point is infinitely small, a raster grid cell is associated with an area of the Earth's surface. These two constraints--a regular grid and grid cells which reference an area--introduce ambiguities and uncertainties when raster data are coerced into a new map projection.

! Some GIS software packages allow a raster to have rectangular grid cells (e.g. GRASS, Idrisi, IPW), while some require that grid cells be square (e.g. Arc/Info). The following discussion will assume that grid cells are square.

1. Grid cell size

For raster datasets using geographic coordinates (i.e. the plate carree projection), a raster image will have a constant cell size in map projection units, e.g. 30 arc-seconds, but these grid cells represent different areas of the Earth's surface. A distance of 30 arc-seconds in the east-west direction decreases with distance from the equator, finally reaching zero at the poles.

Let's compute the dimensions of a 30-arc-second grid cell at various locations on the Earth. We'll assume that the Earth is a sphere with radius 6,371 km (this is a commonly-used value for approximating the Earth as a sphere [Robinson, et al 1984]).

The circumference of the earth, 2*pi*R, is 2*3.14159*6371, or 40,030.17 km. A circle has 360 degrees of arc, so one degree of arc is 40,030.17 / 360, or about 111.19 km long. This is the (approximate) length of one degree of arc measured along a great circle (the Equator or a meridian). One degree contains 60 minutes * 60 seconds/minute, or 3,600 seconds, so 30 arc-seconds is 111.19 * (30/3600) = 0.9266 km or about 927 m.

Thus our 30 arc-second grid cell, at the equator, measures about 927 x 927 m. The north-south dimension of the grid cell, since it falls on a great circle, will always be this distance. The east-west dimension, however, decreases with latitude to a value of zero at the North and South Poles. The decrease varies with the cosine of the latitude [cos(0deg) = 1.0; cos(90deg) = 0.0]. So at 30deg latitude, the width of a grid cell is 927 * cos(30deg) = 927 * 0.8660 = 803 m. At 45deg latitude the cell width is 655 m, and at 60deg, the width is 464.

For a more concrete example, let's assume that you download 30 arc- second digital elevation data from the USGS GTOPO30 dataset,
[outdated link removed] and that you extract a DEM of the contiguous USA. The actual area of these 30 arc-second grid cells will vary from a maximum of 927 x 843 m at Key West, Florida (latitude 24.595deg); to a minimum of 927 x 604 m at the northern boundary of Minnesota (latitude 49.356deg).

The variable area of the 30 arc-second cells presents a dilemma if the data are converted to a different map projection. What is the appropriate choice of cell size if we project this DEM to an Albers equal-area conic projection? This question has no definitive answer. One approach would be to use the finest resolution of the input data in order to avoid losing any information. In this case we would perhaps choose a cell size of 604 x 604 m for the Albers grid. The downside of this approach is that it creates redundancy, a large number of output grid cells, and the illusion that the Albers dataset contains higher- resolution data than the original dataset. Another approach is to use the coarsest resolution of the input dataset and choose a cell size of 927 x 927 m. The downside of this approach is that information is lost in regions where the input data are of higher resolution (e.g. 927 x 604 m). A third approach would be to choose a cell size close to the average cell size of the input data, perhaps by computing the area of a cell in the center of the USA.

2. Resampling method

If you take a regular grid of points on a given projection, and project them to a different projection, the resulting point pattern will not line up perfectly with the original regular grid. Figure 7 illustrates this situation with a set of points spaced at 30 arc-minute intervals. These points were projected to the US Albers projection, and the points from both projections are plotted together for two regions of the US. Note how the Albers points do not coincide neatly with the regular spacing of the 30 arc-minute points.

Suppose that we have a 30 arc-minute grid of the USA (a raster version of the 30 arc-minute point set of Figure 7), and we want to project it to a US Albers projection with a 1000 x 1000 m cell size. We know from Figure 7 that there is no way to lay down a regular grid of 1000 x 1000 m cells so that each Albers cell matches up with a 30-minute cell. The method for determining the value of an output cell is known as resampling.

Most GIS packages support three resampling methods when projecting raster data:

1) Nearest neighbor: The output cell is assigned the value of the nearest input cell. For categorical data, this method is the only choice. 2) Bilinear interpolation: The output cell value is computed as the weighted average of the nearest 4 input cells. This method results in a smoother surface than the nearest- neighbor method. 3) Cubic convolution: The output cell value is computed by fitting a smooth surface to the nearest 16 input cells. This method tends to smooth data more than the bilinear interpolation method.

Figure 8 shows the results of projecting 30 arc-second cells in NW Oregon to a 100 m US Albers grid, using three different resampling methods. Note how bilinear interpolation and cubic convolution create a smoother surface than the nearest neighbor method.

Follow-up Units

- UNIT 52 - Project management
- UNIT 53 - Communicating about and distributing GIS products

Resources

[outdated links have been removed]

Robinson, A. H., Sale, R. D., Morrison, J. L., Muehrcke, P. C., 1984. Elements of Cartography, Fifth Edition. New York: John Wiley & Sons.

Snyder, J.P., and R.M. Voxland, 1989. "An album of map projections", USGS Professional Paper 1453, 249 p.

Snyder, John P. 1987. Map Projections, A Working Manual. Washington, DC: US Government Printing Office.

A general introduction to map projections:
Map Projection Home Page, Hunter College, New York, NY.

This site has many, many images of various map projections and explanatory graphics:
Map Projection Overview, Peter H. Dana, Univ. of Texas at Austin.

A detailed treatment of map datums, also with many useful graphics:
Geodetic Datum Overview, Peter H. Dana, Univ. of Texas at Austin.

A comprehensive overview of geodesy, the study of the size and shape of the earth:
Geodesy for the Layman, National Imagery and Mapping Agency (NIMA).

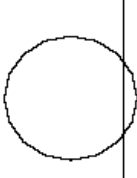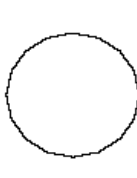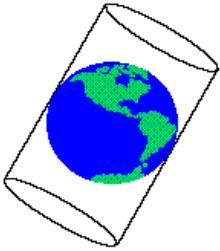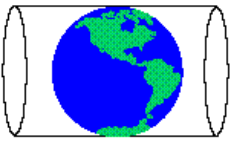*Created: May 14, 1997. Last updated: October 5, 1998.*

Map Projection Surfaces
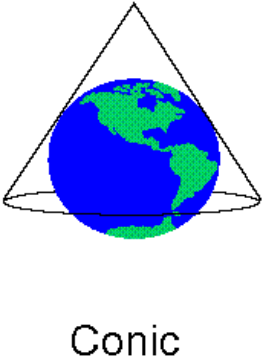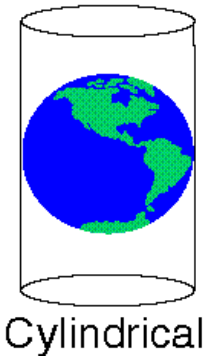
Cylindrical   Conic   Azimuthal

Orientation

Transverse   Oblique   Tangent   Secant

R. Dodson, 8/97

Figure 1

Mercator
Projection

Mercator area (distorted)
34,550,620 km²
2,998,830 km²

R. Dodson, 8/97

Figure 2

Figure 3

Digital Elevation Model
10-km grid, US Albers projection
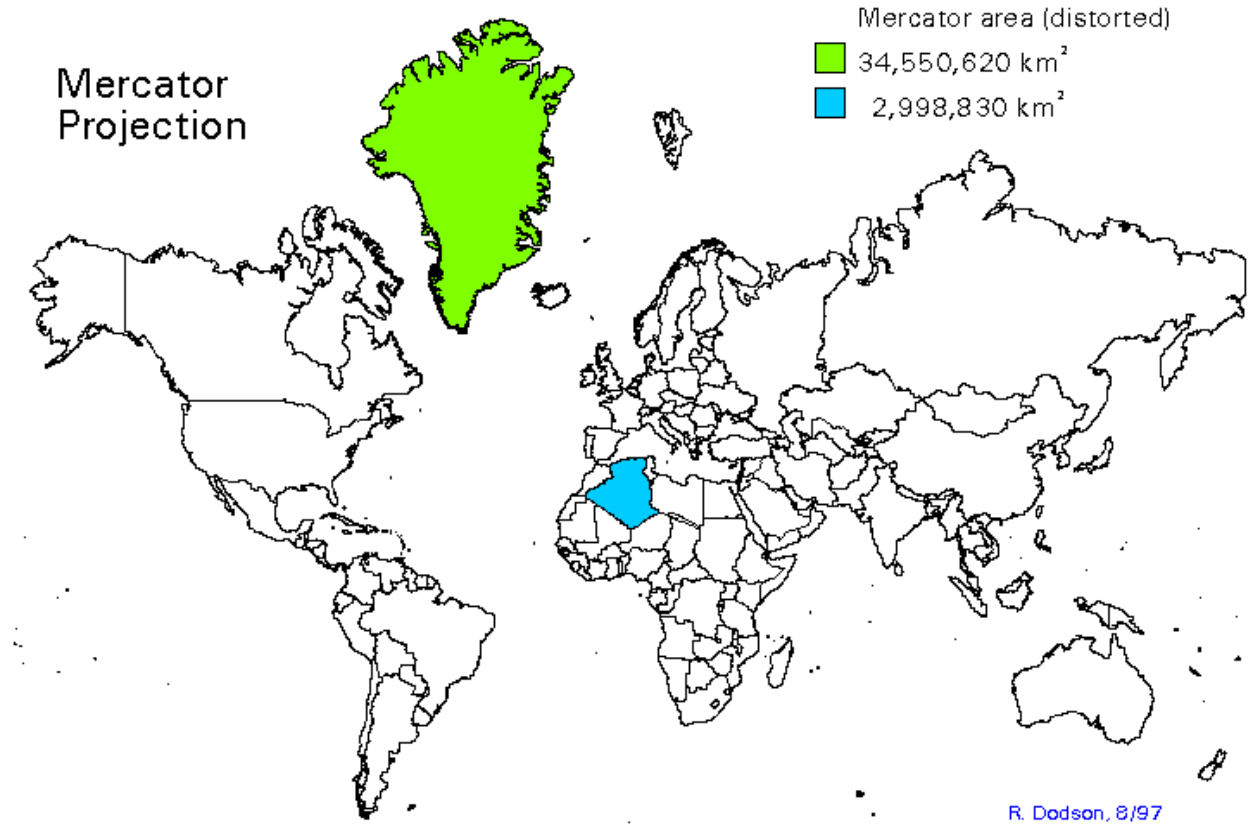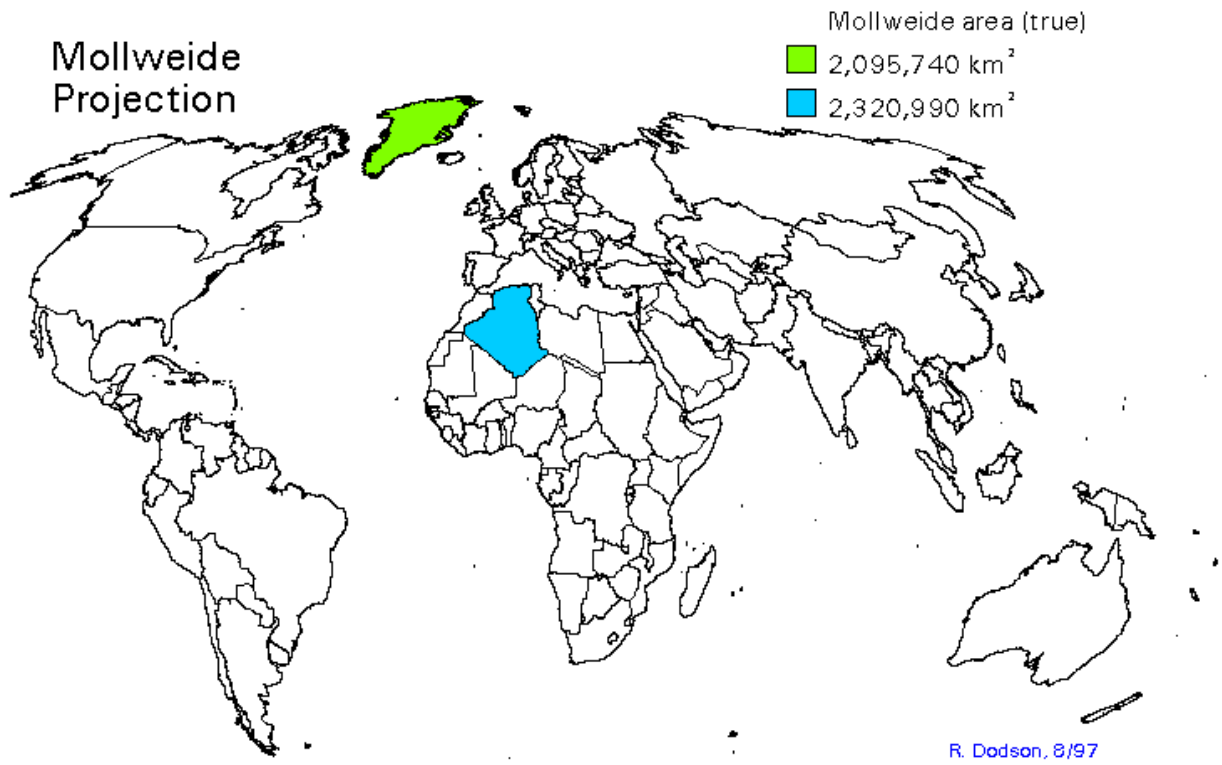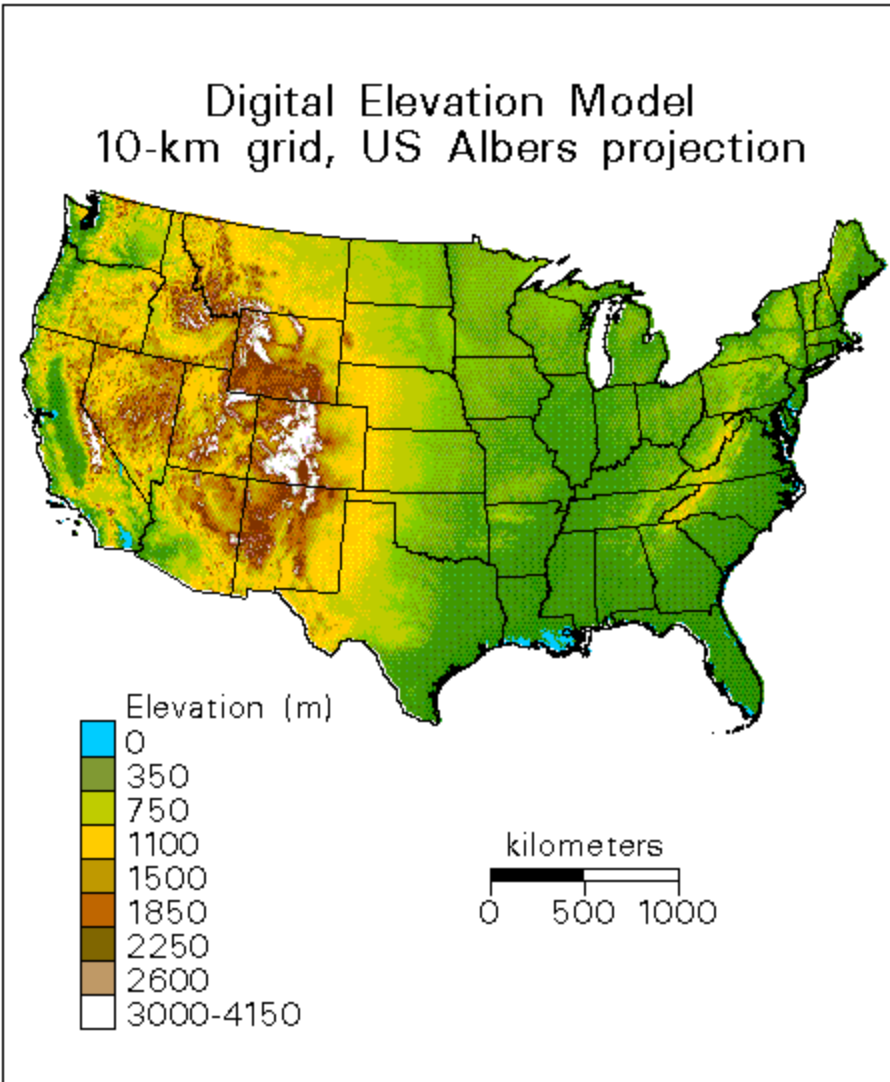
Figure 4

UTM zones of the contiguous USA
Base projection: Albers equal-area conic.
Dashed lines are zone centers.

UTM Zone: 10 11 12 13 14 15 16 17 18 19

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Figure 5

Area distortion in 7.5-minute quadrangles
UTM zone 10, Pacific Northwest, USA
Quadrangles are assumed to be plane trapezoids.
Data generated with TRUE75.AML by G. Daumiller.

Errors computed as:
(True_area - GIS_area)
/ True_area * 100

Percent Error
-2.60 to -2.00
-2.00 to -1.50
-1.50 to -1.00
-1.00 to -0.50
-0.50 to -0.20
-0.20 to 0.00
0.00 to 0.04
0.05 to 0.07
0.07 to 0.08

UTM Zone 10 Center
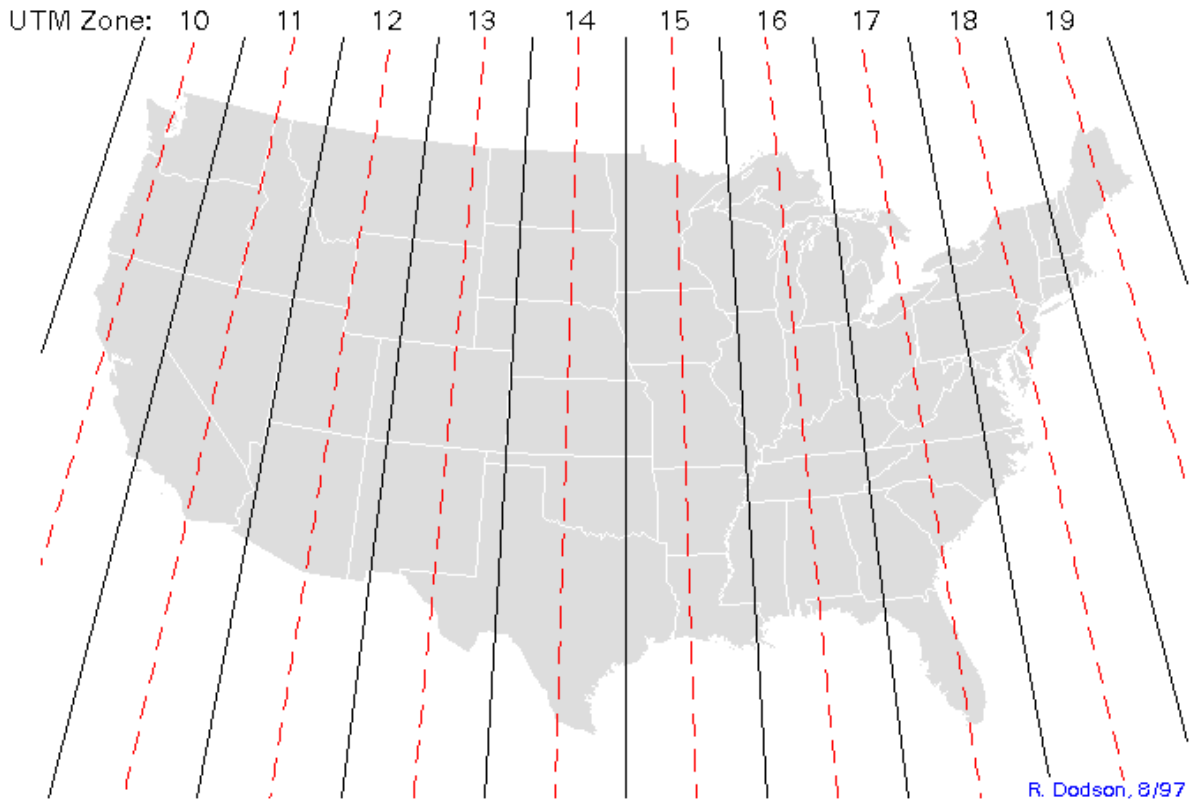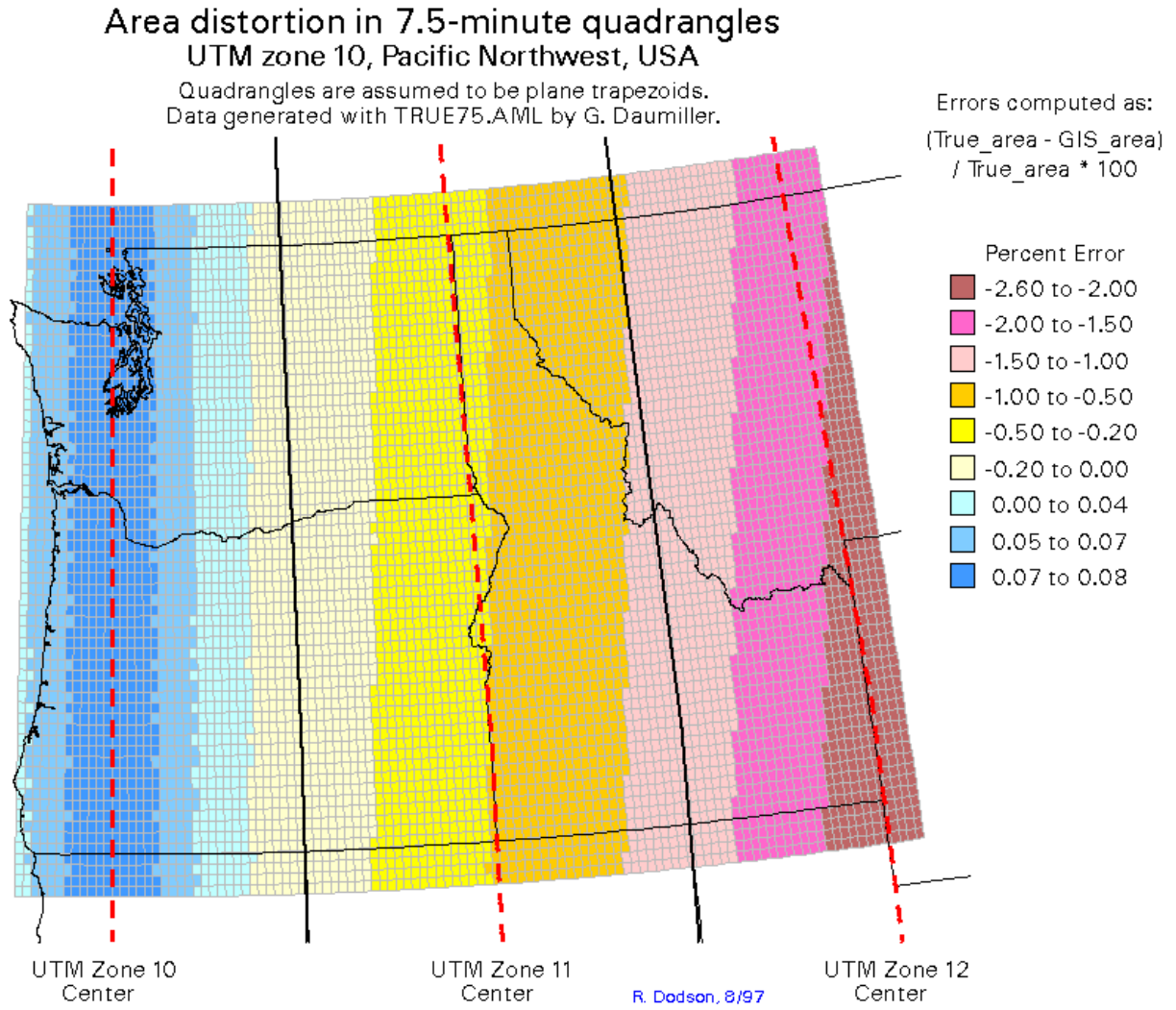UTM Zone 11 Center
UTM Zone 12 Center

R. Dodson, 8/97

Figure 6

Projection Task

The following is a listing of how to do this using arc info. All commands for Arc Info will be printed in bold here. Wherever the word "cover" appears, enter the name of the coverage in current working directory. The online documentation provided by ArcInfo provides parameters, and other technical information required to properly perform this task.

```
Arc: project cover world_geo memphis_equ

*************************************************
*      The INPUT projection has been defined.     *
*************************************************

Use OUTPUT to define the output projection and END to finish.

Project: OUTPUT
Project: PROJECTION AZIMUTHAL
Project: UNITS METERS
Project: PARAMETERS
radius of the sphere of reference   [ 0.00000 ]: 6370997
longitude of center of projection [ 0 0 0.000 ]: -90 0 25
latitude of center of projection  [ 0 0 0.000 ]: 35 6 22
false easting (meters)              [ 0.00000 ]: 0
false northing (meters)             [ 0.00000 ]: 0
Project: END
```

NOTE: The above value of 6370997 m is Arc/Info's default sphere radius.

Projection Task

The following is a listing of how to do this using arc info. All commands for Arc Info will be printed in bold here. Wherever the word "cover" appears, enter the name of the coverage in current working directory. The online documentation provided by ArcInfo provides parameters, and other technical information required to properly perform this task.

```
Arc: PROJECT COVER WORLD_GEO MEMPH_MEX

**************************************************
*      The INPUT projection has been defined.    *
**************************************************

Use OUTPUT to define the output projection and END to finish.

Project: OUTPUT
Project: PROJECTION TWO_POINT_EQUIDISTANT
Project: UNITS METERS
Project: PARAMETERS
Longitude of point A [ 0 0 0.000 ]: -99 3 14
Latitude of point A  [ 0 0 0.000 ]: 19 29 20
Longitude of point B [ 0 0 0.000 ]: -90 0 25
Latitude of point B  [ 0 0 0.000 ]: 35 6 22
Project: END
```

Figure 7

Projecting raster data from Latitude/Longitude coordinates to Albers equal-area conic, using three resampling methods
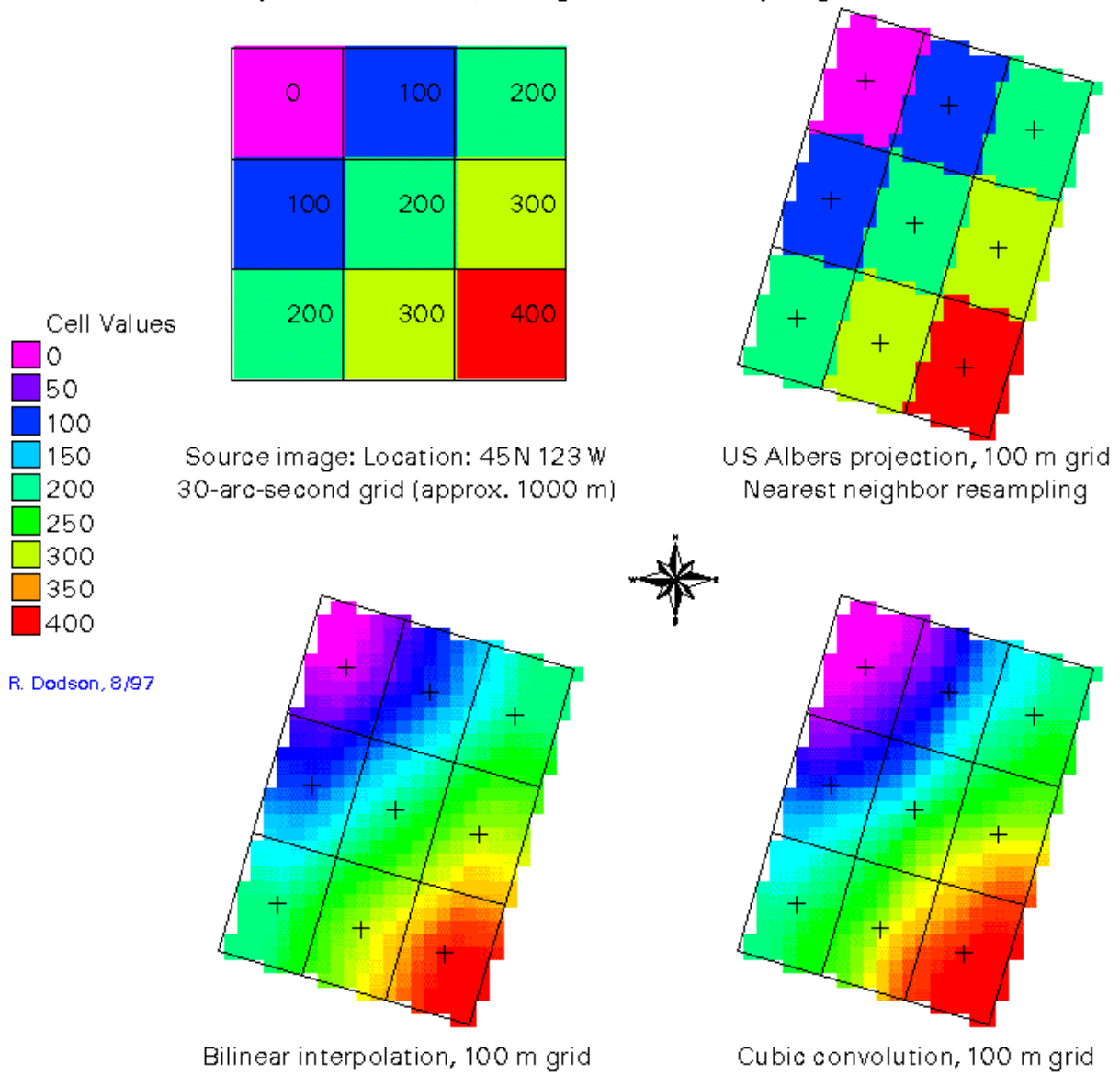

Source image: Location: 45 N 123 W
30-arc-second grid (approx. 1000 m)

US Albers projection, 100 m grid
Nearest neighbor resampling

Cell Values
- 0
- 50
- 100
- 150
- 200
- 250
- 300
- 350
- 400

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Bilinear interpolation, 100 m grid

Cubic convolution, 100 m grid

Figure 8