## Chapter 11. Coordinate Systems

Objectives:

- Learning the basic properties and uses of coordinate systems
- Understanding the difference between geographic coordinates and projected coordinates
- Getting familiar with different types of map projections
- Managing and troubleshooting coordinate systems of feature classes and images


## GeOreferencing

- GOAL: To assign a location to all the features represented in our geographic information data
- In order to do so, we need to make use of the following elements:
- ellipsoid/geoid
- datum
- projection
- coordinate system
- scale


To determine a position on the Earth, you'll need to understand how these elements relate to each other in order to specify a position

- During the next few lectures you will be introduced to these elements


## Coordinate Systems

- A coordinate system is a standardized method for assigning numeric codes to locations so that locations can be found using the codes alone.
- Standardized coordinate systems use absolute locations.
- In a coordinate system, the x-direction value is the easting and the $y$-direction value is the northing. Most systems make both values positive.


## What is a Map?

## Definition of Maps:

- A graphic depiction on a flat medium of all or part of a geographic realm in which real world features have been replaced with symbols in their correct spatial location at a reduced scale.
-To map is to transform information from one form to another --- Mathematics

-Earth surface $\xrightarrow{\text { map }}$ Paper --- Geography


## Models of the Earth

A Sphere


An Ellipsoid


## Earth Shape: Sphere and Ellipsoid



Pole to pole distance: 39,939,593.9 meters Around the Equator distance: 40,075,452.7 meters

## Earth Shape: Sphere and Ellipsoid

- The sphere is about 40 million meters in circumference.
- An ellipsoid is an ellipse rotated in three dimensions about its shorter axis.
- The earth's ellipsoid is only $1 / 297$ off from a sphere.
- Many ellipsoids have been measured, and maps based on each. Examples are WGS84 and GRS80.


## Ellipticity of the Earth

-How far is the Earth from being a perfect sphere?


- Using these two axes’ lengths we can calculate the ellipticity (flattening) of an ellipsoid, with $f=0$ being a perfect sphere and $f=1$ being a straight line


## Ellipticity of the Earth



- $\mathrm{a}=$ semi-major axis
- b = semi-minor axis
- $f=[(a-b) / a]=$ flattening


## Ellipticity of the Earth

-Newton estimated the Earth's ellipticity to be about $f=1 / 300$

- Modern satellite technology gives an $f=$ 1/298 (~0.003357)

Examples of ellipsoid flattening (f)
$\prod_{\text {These small values of }}$ $f$ tell us that the Earth is very close to being a sphere, but not close enough to ignore its ellipticity if we want to accurately locate features on the Earth


## The Earth as a Geoid

- Rather than using a regular shape like an ellipsoid, we can create a more complex model that takes into account the Earth's irregularities
- The only thing shaped like the Earth is the Earth itself, thus the term Geoid, meaning "Earth like"
- Its shape is based on the Earth's gravity field, correcting for the centrifugal force of the earth's rotation.



## The Earth as Geoid

- Geoid $\rightarrow$ The surface on which gravity is the same as its strength at mean sea level
- Geodesy is the science of measuring the size and shape of the earth and its gravitational and magnetic fields.



## Geodetic Datum

- In order to manage the complexities of the shape of a geoid model of the Earth, we use something called a geodetic datum
- Datum -- n. (dat - m) \any numerical or geometric quantity which serves as a reference or base for other quantities
- A geodetic datum is used as a reference base for mapping
- It can be horizontal or vertical
- It is always tied to a reference ellipsoid


## Datums

- An ellipsoid gives the base elevation for mapping, called a datum.
- North American Datum 1927 (NAD27)
- North American Datum 1983 (NAD83)
- Particular datums are based on specific spheroids:
- NAD27 is based on the Clarke 1866 spheroid
- NAD83 is based on the GRS_1980 spheroid
- Conversions between datums are called transformations


## Earth Models and Datums



Figure 2.4 Elevations defined with reference to a sphere, ellipsoid, geoid, or local sea level will all be different. Even locations as latitude and longitude will vary somewhat. When linking field data such as GPS with a GIS, the user must know what base to use.

## Geoid


-105.0 85.0 Meter

## Geographic Coordinates

- We can use geographic coordinates (i.e. latitude \& longitude) to specify locations
- Treating the Earth as a sphere is accurate enough for small maps of large areas of the Earth (i.e. very small scale maps)



## Geographic Coordinates

- Latitude and longitude are based on the spherical model of the Earth
- This is the most commonly-used coordinate system (i.e. you will have seen it on globes or largescale maps)



## Geographic Coordinates

- Lines of latitude are called parallels
- Lines of longitude are called meridians


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## The Graticule

- The parallels and meridians of latitude and longitude form a graticule on a globe, a grid of orthogonal lines



## Geographic Coordinates

$90^{\circ}$ North Latitude

$90^{\circ}$ South Latitude
Figure 2.6 Geographic coordinates. The familiar latitude and longitude system, simply converting the angles at the earth's center to coordinates, gives the basic equirectangular projection. The map is twice as wide as high ( $360^{\circ}$ east-west, $180^{\circ}$ north-south).

## Geographic Coordinates

- The Prime Meridian and the Equator are the origin lines used to define latitude and longitude



## The Prime Meridian (1884)



## Geographic Coordinates

- Geographic coordinates are calculated using angles
- Units are in degrees, minutes, and seconds
- Any location on the planet can be specified with a unique pair of geographic coordinates



## Latitude \& Longitude on an Ellipsoid

- On a sphere, lines of latitude (parallels) are an equal distance apart everywhere
- On an ellipsoid, the distance between parallels increases slightly as the latitude increases



## Geographic Coordinates as Data



Figure 2.12 Part of the World Data Bank I listing of the coordinates of the coastline of Africa. Format is geographic coordinates in decimal degrees.

## Using Projections to Map the Earth

 -We have discussed geodesy, and we now know about modeling the shape of Earth as an ellipsoid and geoid -We are ready to tackle the problem of transforming the 3dimensional Earth $\rightarrow$ 2-dimensional representation that suits our purposes:Earth surface Paper map or GIS


## What is a Projection?

- Map projection - The systematic transformation of points on the Earth's surface to corresponding points on a planar surface

-The easiest way to imagine this is to think of a light bulb inside of a semi-transparent globe, shining features from the Earth's surface onto the planar surface



## Projections Distort

- Because we are going from the 3D Earth $\rightarrow$ 2D planar surface, projections always introduce some type of distortion
- When we select a map projection, we choose a particular projection to minimize the distortions that are important to a particular application



## Three Families of Projections

- There are three major families of projections, each tends to introduce certain kinds of distortions, or conversely each has certain properties that it used to preserve (i.e. spatial characteristics that it does not distort):
- Three families:

1. Cylindrical projections
2. Conical projections
3. Planar projections


Figure 2.7 The earth can be projected in many ways, but basically onto three shapes that can be unrolled into a flat map: a flat plane, a cylinder, and a cone.

## The Graticule

- Picture a light source projecting the shadows of the graticule lines on the surface of a transparent globe onto the developable surface ...

Cylinder


Cone


Plane


## The Graticule, Projected

GLOBE GRATICULE


CYLINDRICAL GRATICULE


CONIC GRATICULE


PLANAR (AZIWIUTHAL) GRATICULE


## Tangent Projections


-Tangent projections have a single standard point (in the case of planar projection surfaces) or a standard line (for conical and cylindrical projection surfaces) of contact between the developable surface and globe

## Secant Projections



Secant Cylindrical Projection



Secant Planar Projection

- Secant projections have a single standard line (in the case of planar projection surfaces) or multiple standard lines (for conical and cylindrical projection surfaces) of contact between the developable surface and the globe


## Secant Map Projections

Figure 2.9
Variations on the
Mercator
(pseudocylindrical) projection shown as secant

Equatorial


Transverse


## Standard Parallels



Figure 2.8 Standard parallels. The conic projection cuts through the globe, and the earth is projected both in and out onto it. This is a secant conic projection. Lines of true scale, where the cylinder and sphere touch, become standard parallels. If the touching is along one line, the projection is tangent and has one standard parallel.

## Map Projections (continued)

- Projections can be based on axes parallel to the earth's rotation axis (equatorial), at 90 degrees to it (transverse), or at any other angle (oblique).
- A projection that preserves the shape of features across the map is called conformal.
- A projection that preserves the area of a feature across the map is called equal area or equivalent.
- No flat map can be both equivalent and conformal. Most fall between the two as compromises.
- To compare maps in a GIS, both maps MUST be in the same projection.


## No flat map can be both equivalent \& conformal.



Figure 2.9 Examples of projections classified by their distortions. Conformal projections preserve local shape, equivalent projections preserve area, while compromise projections lie between the two. No projection can be equivalent and conformal.

## Preservation of Properties

- Every map projection introduces some sort of distortion because there is always distortion when reducing our 3dimensional reality to a 2-dimensional representation
- Q: How should we choose which projections to use?

A: We should choose a map projection that preserves the properties appropriate for the application, choosing from the following properties:

1. Shape
2. Area
3. Distance
4. Direction

Note: It may be more useful to classify map projections by the properties they preserve, rather than by the shape of their surfaces

## Preservation of Properties - Shape

- If a projection preserves shape, it is known as a conformal projection
- preserves local shape (i.e. angles of features)
- graticule lines have $90^{\circ}$ intersection
- distortion of shape, area over longer distances
- rhumb lines
- lines of constant direction


Greenland (Globe)
Greenland (Mercator)

## Preservation of Properties - Area

- Equal Area Projections
- preserve the area of displayed features
- however, shape, distance, direction, or any combination of these may be distorted
- on large-scale maps, the distortion can be quite difficult to notice


Albers Equal-Area Conic

A projection cannot preserve both shape and area!

## Preservation Properties - Distance

- Equidistant Projections
- preserve the distance between certain points
- they maintain scale along one or more lines
- display true distances


A projection cannot preserve distance everywhere!

## Preservation Properties - Direction

- Azimuthal Projections
- preserve directions, or azimuths, of all points on the map with respect to the center
- They can also be
- conformal
- equal-area
- equidistant


Lambert Equal-Area Azimuthal

A projection cannot preserve direction everywhere!

## Coordinate Systems

- We have addressed both the issue of how to model the shape of the 3-dimensional Earth as an ellipsoid/geoid, and how to transform spatial information from the Earth's surface to a 2dimensional representation using the projection process
- Our remaining task is to conceive of some system by which we can precisely specify locations on a projected map that correspond to actual locations on the surface of the Earth $\rightarrow$ For this, we need to use some coordinate system


## Coordinate Systems

- A coordinate system is a standardized method for assigning codes to locations so that locations can be found using the codes alone.
- Standardized coordinate systems use absolute locations.
- In a coordinate system, the $x$-direction value is the easting and the $y$-direction value is the northing. Most systems make both values positive.


## The Geographic Coordinate System

 Viewing latitude and longitude angles from a 3D perspective:

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## Planar Coordinate Systems

- Once we start working with projected spatial information, using latitude and longitude becomes less convenient
- We can instead use a planar coordinate system that has $x$ and $y$ axes, an arbitrary origin (a Cartesian plane), and some convenient units (e.g. ft. or m.)
- When applied in a geographic context:
- Eastings are $x$ values
- Northings are $y$ values



## Raster Coordinate Systems

- A raster that has been assigned a real world coordinate system is said to have been georeferenced. There are two common ways to get to this state:
- Case I: All of the parameters (projection, datum, cell size, and x-y coordinates of the upper left corner of the raster) are known, and this merely needs to be applied to the dataset
- Case II: The coordinate system parameters are completely unknown, and the process of geometric correction is required to change the geometric/spatial properties of the image data so that we can accurately project the image, a.k.a.
- image rectification


## Geometric Correction

- Four Basic Steps of Rectification

1. Collect ground control points (GCPs)

Points in the image for which you can determine real-world coordinates
2. Create equations relating the image pixel coordinates at those GCPs to their real-world coordinates
3. Transform the pixel coordinates based on the equations
4. Resample the pixel values (BVs) from the input image to put values in the newly georeferenced image

## Geometric Correction

- Three Types of Resampling
- Nearest Neighbor - assign the new BV from the closest input pixel. This method does not change any values.
- Bilinear Interpolation - distanceweighted average of the BVs from the 4 closest input pixels
- Cubic Convolution - fits a polynomial equation to interpolate a "surface" based on the nearest 16 input pixels; new BV taken from surface



## Universal Transverse Mercator

- Earlier, you were introduced to the Transverse Mercator projection
- That projection is used as the basis of the UTM coordinate system, which is widely used for topographical maps, satellite images, and many other uses
- The projection is based on a secant transverse cylindrical projection

- Recall that this projection uses a transverse cylinder that has standard lines that run northsouth, and distortion increases as we move further east or west



## Universal Transverse Mercator

- In order to minimize the distortion associated with the projection, the UTM coordinate system uses a separate Transverse Mercator projection for every 6 degrees of longitude $\rightarrow$ the world is divided into 60 zones, each 6 degrees of longitude in width, each with its own UTM projection:



## Universal Transverse Mercator

## UTM Zone Numbers



## Universal Transverse Mercator

- The central meridian, which runs down the middle of the zone, is used to define the position of the origin
- Distance units in UTM are defined to be in meters, and distance from the origin is measured as an Easting (in the xdirection) and a Northing (in the ydirection)
- The x-origin is west of the zone (a false easting), and is placed such that the central meridian has an Easting of 500,000 meters



Figure 2.14 The universal transverse Mercator coordinate system.

## UTM Zones in the Lower 48



Figure 2.13 Universal transverse Mercator zones in the 48 contiguous states.

## State Plane Coordinate Systems

- Each state in the U.S. has its own planar coordinate system(s) known as State Plane Coordinate Systems (SPCS)
- Depending on the size of the state, its coordinate system may be divided into multiple zones (e.g. Alaska has 8 zones)
- These may make use of three different projections, depending on the shape of the state:
- Lambert Conformal Conic
- Transverse Mercator
- Oblique Mercator


## State Plane Coordinate Systems



## State Plane Coordinate Systems Massachusetts (feet)

Units: Feet


## State Plane Coordinate Systems Massachusetts (feet)



# Next Topic: 

Presenting GIS Data

