COA 690/790 GIS in Marine Science

Geodesy, Datum, Map Projection, and Coordinate System

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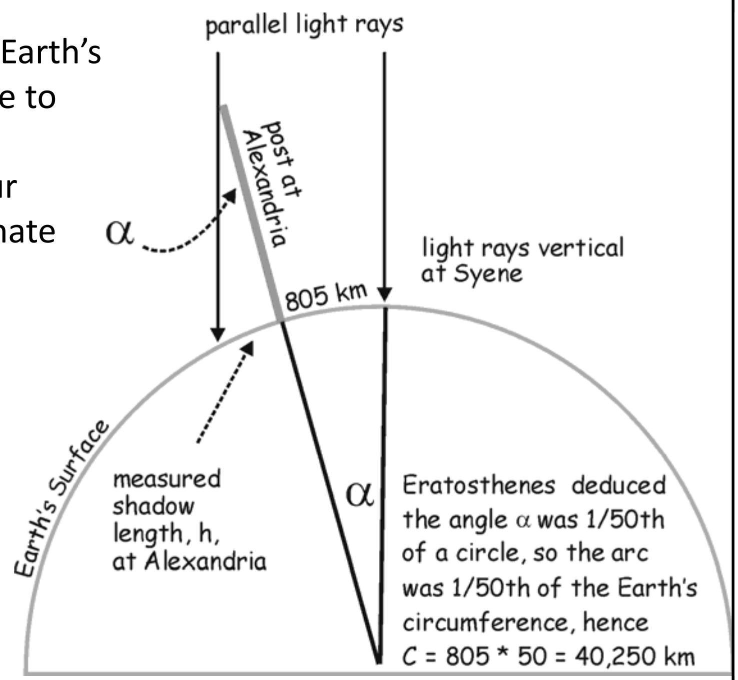
Outline

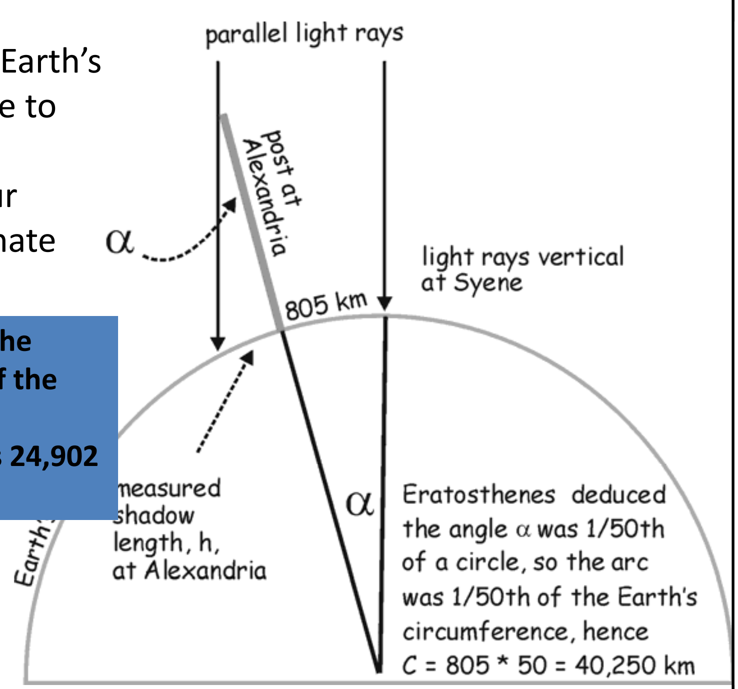
- Ellipsoid
- Datum
  - global
  - local
- Datum transformation
- Projection
- Coordinate system

Eratosthenes deduced the Earth's circumference to within a few percent of our present estimate



Eratosthenes deduced the Earth's circumference to within a few percent of our present estimate

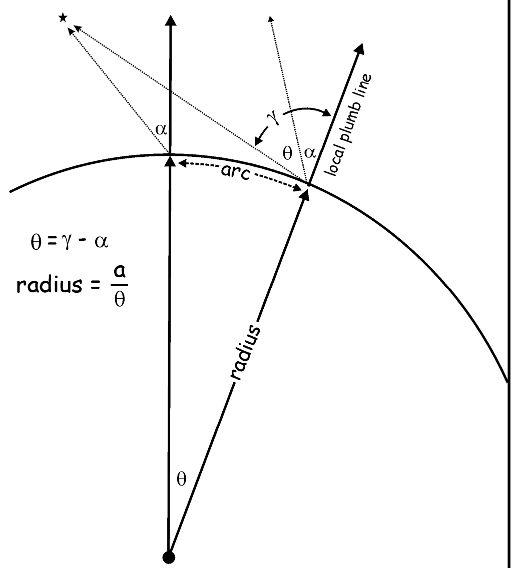
More precisely the circumference of the earth at the equator is 24,902 mi / 40,076 km



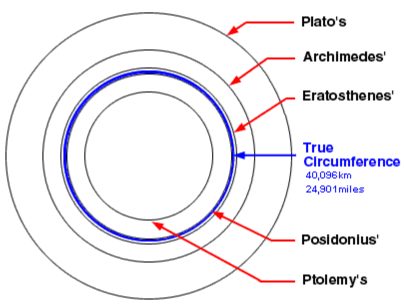
Earth's Size?

Other scholars used stellar location (a zenith angle) to estimate Earth size. (Posidonius – 38,600 km)

Some were accurate, but a shorter estimate of 28,960 km was adopted by Ptolemy (2nd century) and widely accepted until the 1500's when Gerardus Mercator revised the size estimate upward.



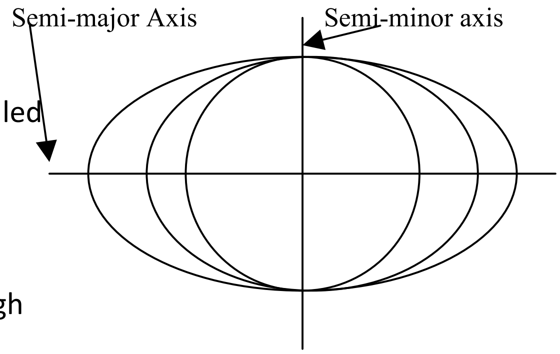
Circumference estimates



With the circumnavigation of the globe and subsequent scientific calculations, the accepted value of the circumference of the earth returned from Ptolemy's calculation back to that of Eratosthenes. After countless millennia, scientists, explorers, clergy, and laymen finally knew the "true shape" and "true size" of the earth. Of course, this geographic euphoria wouldn't last.

Isaac Newton (1670) suggested the earth would be flattened at the poles, due to centrifugal force

Thus, the radius along the axis of rotation would be less than through the equator



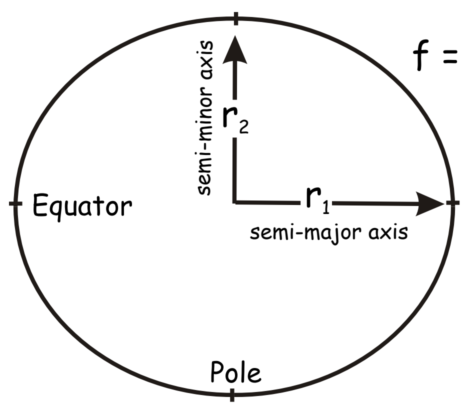
There are two axes are called the

a) semi-major axis (through the equator)

b) semi-minor axis (through the poles)

<u>Earth's is Flattened - an Ellipsoid</u>

Two radii:
r_1, along semi-major (through Equator)
r_2, along semi-minor (through poles)



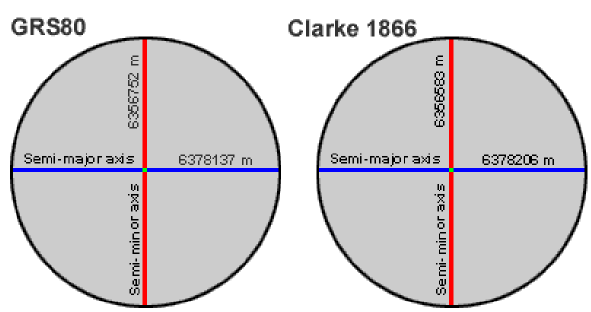
$$f = \frac{r_1 - r_2}{r_1}$$

No one could agree on the right size
- specifically, what were the best estimates of r_1 and r_2?

- Different surveys came up with different estimates, and different countries adopted different “standard” ellipsoids

- Why? Because of irregularities in the Earth’s shape

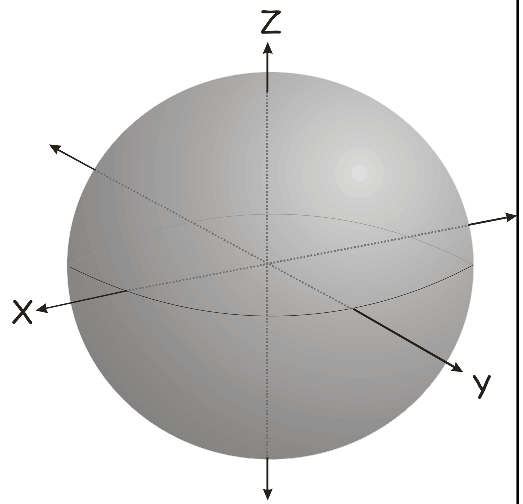
Examples of spheroid



Spheroids created using satellite information, such as GRS80, are starting to replace traditional ground-measured spheroids, such as Clarke 1866. In this example, measurements for both spheroids have been rounded to the nearest meter.

Geocentric Ellipsoid and Coordinate System

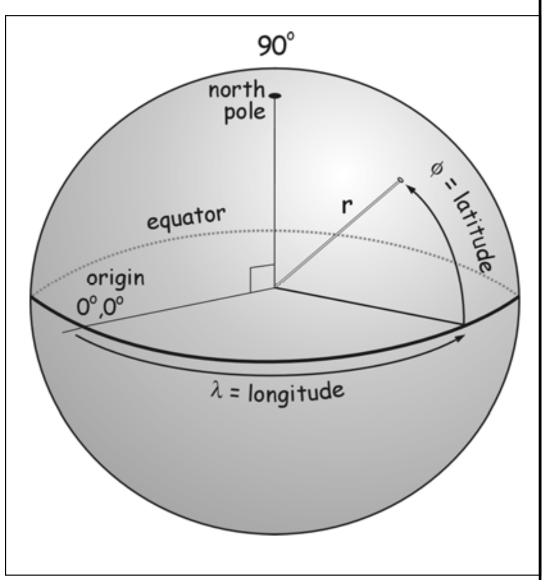
- 3-D system
- Origin (0,0,0) at the Earth center of mass
- Best globally fit spheroid, e.g., WGS84, used for global coordinate systems

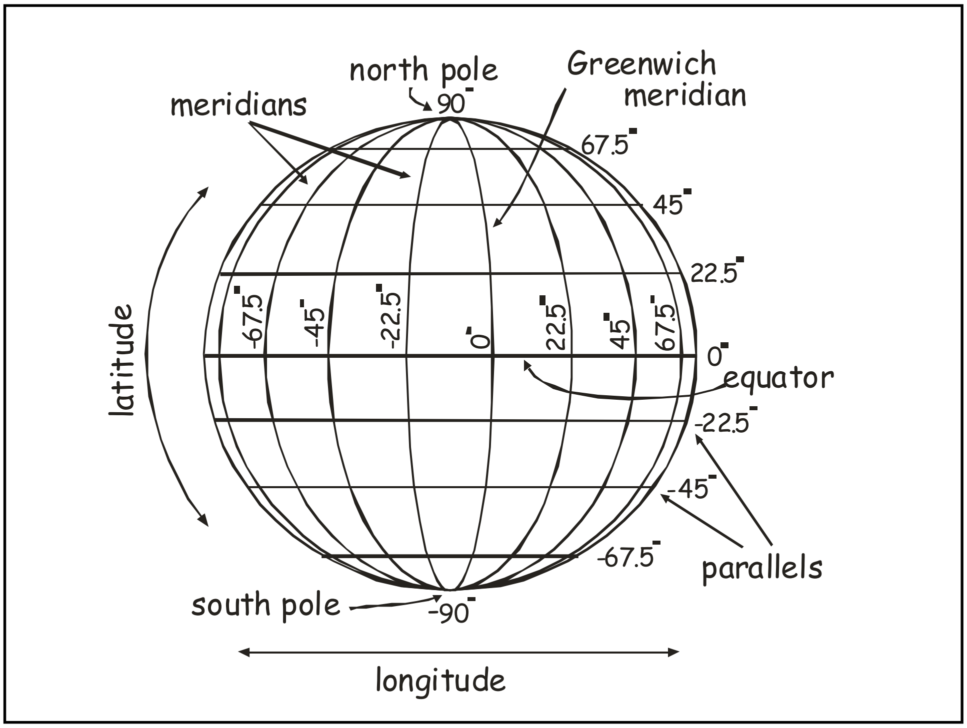


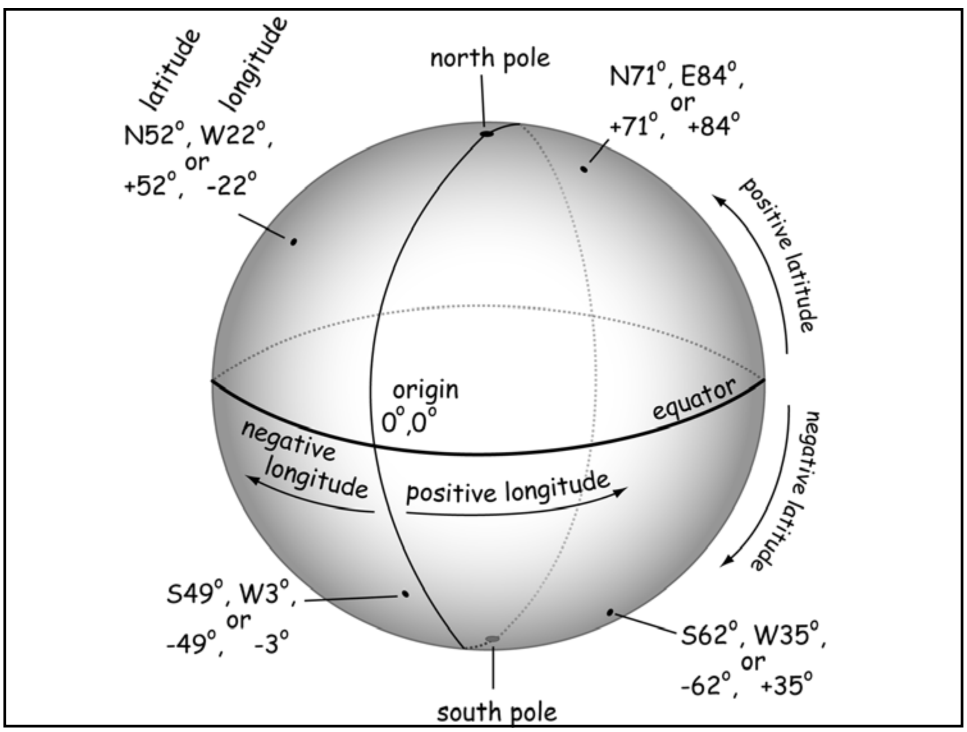
"Horizontal" Position

Our position on the surface of the Earth is defined by a latitude / longitude pair on a specified ellipsoid (also known as a spheroid)

Starting point
North is at the top




north pole
Greenwich meridian
meridians
90°
67.5°
45°
22.5°
0°
equator
-22.5°
-45°
-67.5°
parallels
latitude
-67.5
-45
-22.5
0
22.5
45
67.5
south pole
-90°
longitude


latitude
longitude
north pole
N71°, E84°,
or
+71°, +84°
N52°, W22°,
or
+52°, -22°
positive latitude
origin
0°,0°
equator
negative longitude
positive longitude
negative latitude
S49°, W3°,
or
-49°, -3°
S62°, W35°,
or
-62°, +35°
south pole

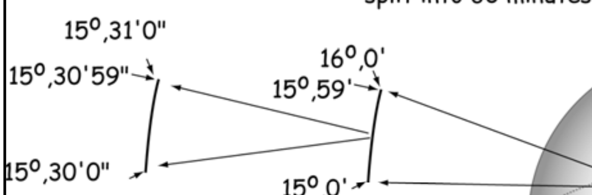
The Equator, Prime Meridian, Tropic of Cancer and Tropic of Capricorn are all **imaginary lines.**

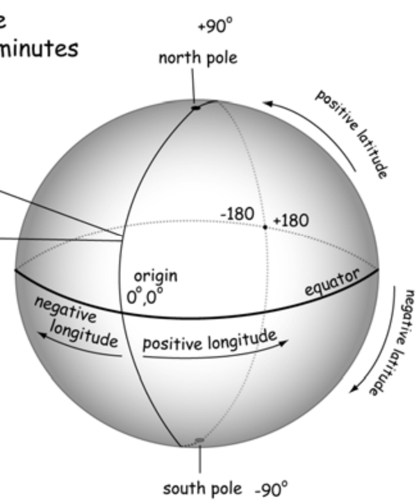
http://images.google.com/imgres?imgurl=http://worldatlas.com/aatlas/newart/imagee.gif&imgrefurl=http://worldatlas.com/aatlas/imagee.htm&h=274&w=583&sz=32&tbnid=r7QeUT5IO1638M:&tbnh=63&tbnw=134&prev=/images%3Fq%3Dtropic%2Bof%2Bcancer%26um%3D1&start=3&sa=X&oi=images&ct=image&cd=3

Degree Units

Each 1 minute is
split into 60 seconds

Each 1 degree
split into 60 minutes





Coordinates are expressed
as
degrees, minutes, seconds

e.g. 15⁰ 30' 59"

or as decimal degrees, e.g., 15.51539⁰

We Can Convert!

DD from DMS
DD = D + M/60 + S/3600
e.g.
DMS = 32° 45' 28"

DD = 32 + 45/60 + 28/3600
= 32 + 0.75 + 0.0077778
= 32.7577778

DMS from DD
D = integer part
M = integer of decimal part x 60
S = 2nd decimal x 60
e.g.
DD = 24.93547
D = 24
M = integer of 0.93547 x 60
= integer of 56.1282
= 56
S = 2nd decimal x 60
= 0.1282 * 60 = 7.692
so DMS is
24° 56' 7.692"

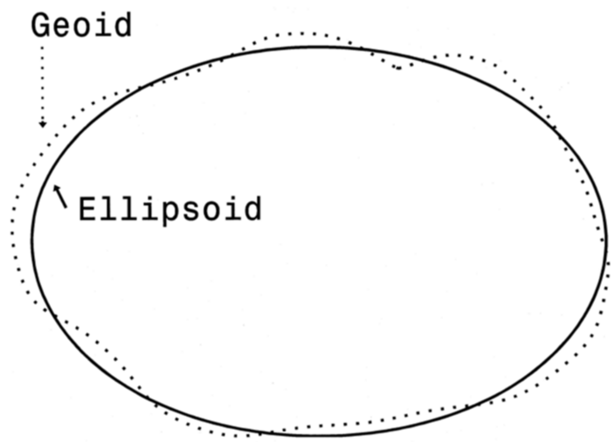
The Earth is NOT an Ellipsoid (only very close in shape)

The Earth has irregularities in it - deviations from a perfectly ellipsoidal shape

These deviations are due to differences in the gravitational pull of the Earth

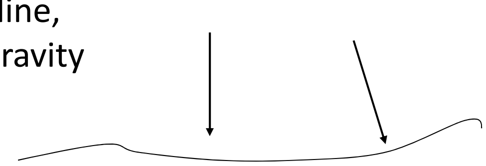
Deviations are NOT the surface topography

The Earth's True Shape is Best Described as a GEOID



Definition of the Geoid

A Geoid is the surface perpendicular to a plumb line, and for which the pull of gravity is a given value



The Geoid is a measured surface (not mathematically defined)

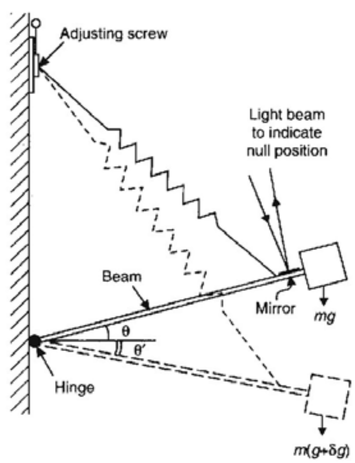
Found via surface instruments (gravimeters) towed behind boats, planes, or in autos

Or, from measurements of satellite paths (ephemerides)

May be thought of as an approximation of mean sea level

The Geoid is a measured surface

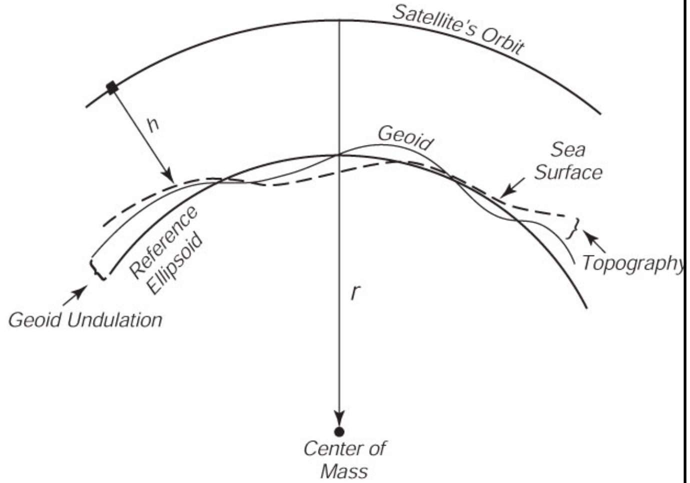
Gravimeter



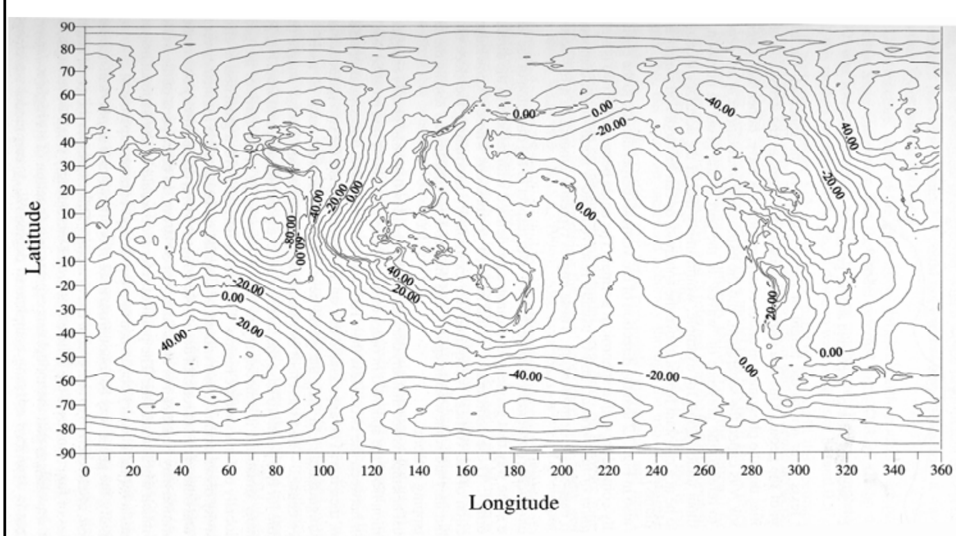
CIRES, U. of Colorado, and Gerd Steinle-Neumann, U. Bayerisches

The Geoid is a measured surface

Gravimeter on a Satellite

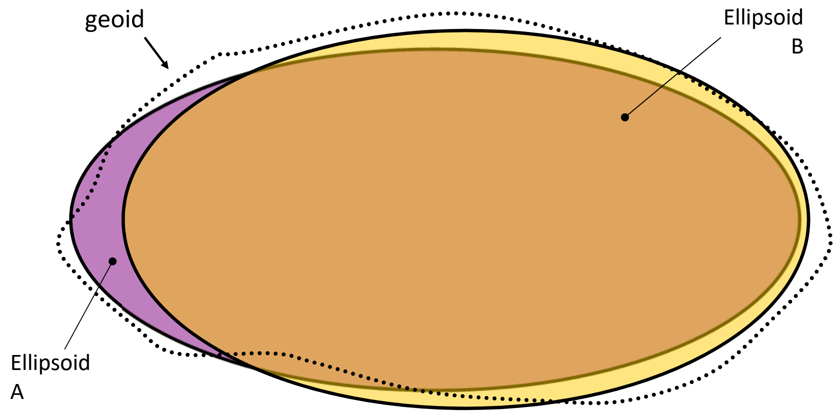


Separation between the Geoid and best-fitting global ellipsoid averages about 30 meters – this "undulation" is always below 100 meters



Different Ellipsoids in Different Countries

There are locally "best fit" ellipsoids



Local or Regional Ellipsoid

Origin, R_1, and R_2 of ellipsoid specified such that separation between ellipsoid and Geoid is small

These ellipsoids have names, e.g., Clarke 1880, or Bessel

Global Ellipsoid

Selected so that these have the best fit "globally", to sets of measurements taken across the globe.

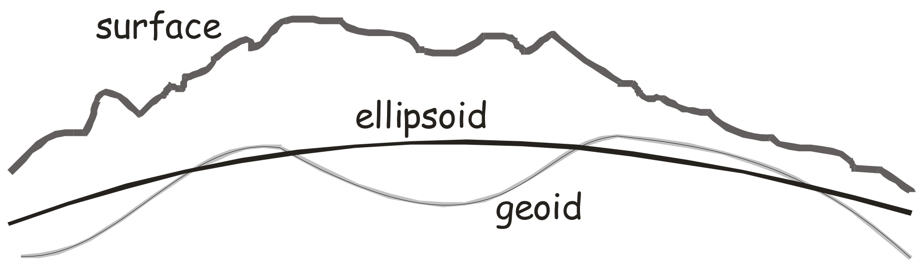
Generally have less appealing names, e.g. WGS84, or ITRF 2000

Table 3-1 Official ellipsoids (from Snyder, 1987)

Name	Year	Equatorial Radius, r_1 meters	Polar Radius, r_2 meters	Flattening Factor f	Users
Airy	1830	6,377,563.4	6,356,256.9	1/299.32	Great Britain
Bessel	1841	6,377,397.2	6,356,079.0	1/299.15	Central Europe, Chile, Indonesia
Clarke	1866	6,378,206.4	6,356,583.8	1/294.98	Most of Africa; France
Clarke	1880	6,378,249.1	6,356,514.9	1/293.46	North America; Philippines
International	1924	6,378,388.0	6,356,911.9	1/297.00	Much of the World
Australian	1965	6,378,160.0	6,356,774.7	1/298.25	Australia
WGS72	1972	6,378,135.0	6,356,750.5	1/298.26	NASA, U.S. Dept. of Defense
GRS80	1980	6,378,137.0	6,356,752.3	1/298.26	Worldwide

We have three surfaces to keep track of at each point on Earth

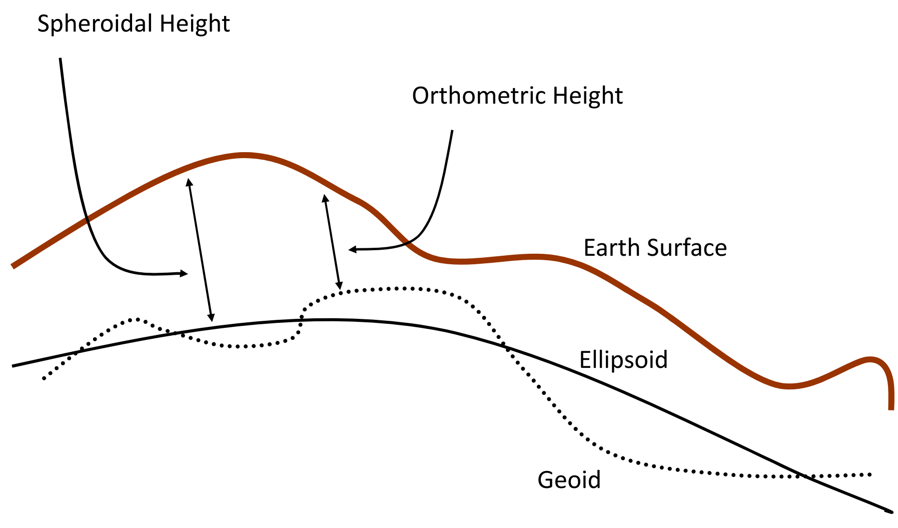
1. the ellipsoid
2. the geoid, and
3. the physical surface



Heights are usually specified relative to the Geoid

Heights above the geoid are *orthometric heights*
These are the heights usually reported on topographic or other maps

Heights above the ellipsoid are spheroidal heights
Sometimes used to define vertical position, but usually to specify geoid-ellipsoid separation



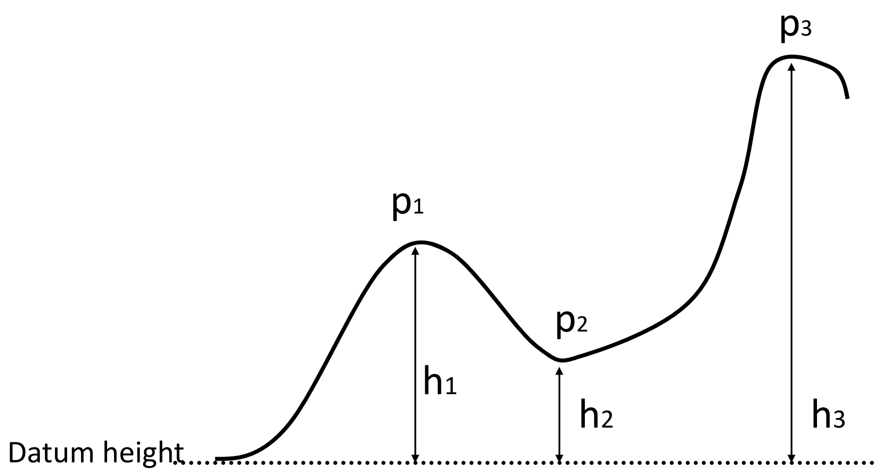
Geodesy - science of measuring the size and shape of the Earth

Datum - a reference surface

e.g., a site datum - a reference height against which elevations are measured

site plan for a subdivision
- establish datum as a fixed elevation at the lowest point on the property. All heights are measured relative to this site (or local) datum

(Ferris State/ACSM)



National or Global Datums

A datum is a reference surface - there may be infinite reference surfaces

Nations or governing bodies can agree on points and surfaces as standard references

Need to specify the size and shape of the surface, and the location of points on the surface

Defining a Datum

Horizontal Datum

Specify the ellipsoid

Specify the coordinate locations of features on this ellipsoidal surface

Vertical Datum

Specify the ellipsoid

Specify the Geoid – which set of measurements will you use, or which model

Specifying a Horizontal Datum

- Measure positions (celestial observations, surveys, satellite tracking)
- Adjust measurements to account for geoid, determine position on adopted ellipsoid

Specifying a Horizontal Datum

A horizontal datum is a reference ellipsoid, plus a precisely-measured set of points that establish locations on the ellipsoid.

These points define the reference surface against which all horizontal positions are measured

Defining the Horizontal Datum

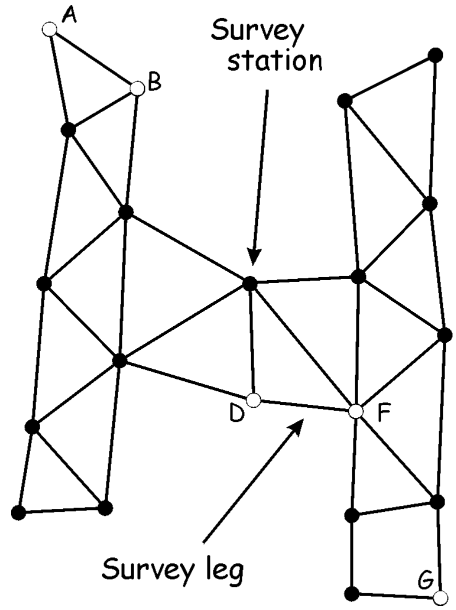
Horizontal datums are determined from the measurement an analysis of large survey networks

1. Define the shape of the Earth (the ellipsoid)
2. Define the location of a set of known points – control points – for which the position on the ellipsoid is precisely known
3. This is the reference surface and network against which all other points will be measured

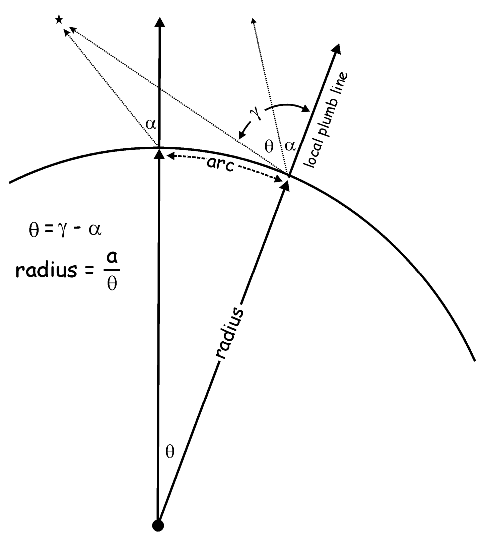
Datum, Survey Network

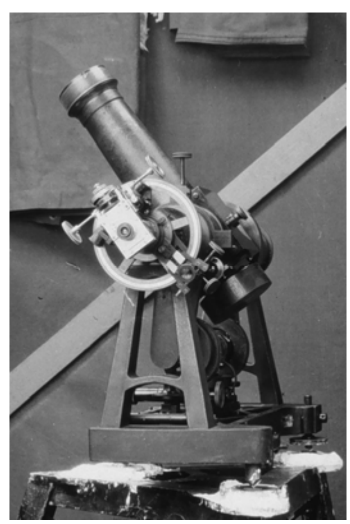
Historically:
- Triangulation Network
- Astronomical observation
- Intermittent baselines
- Multiple, redundant angle measurements

Why these technologies?
- Easy to measure angles
- Difficult to measure distance accurately
- Time consuming to measure point position accurately

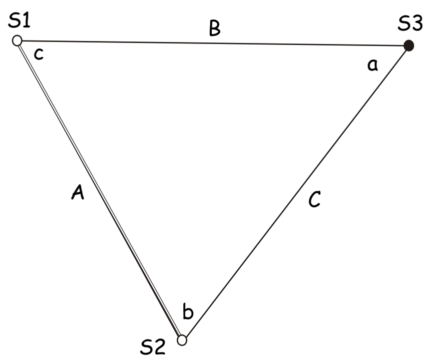


Astronomical Observations Were Accurate, but Time-Consuming





Triangulation

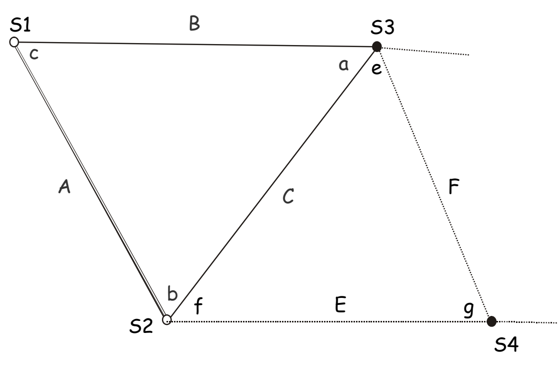


If we measure the initial baseline length A, and measure the angles a, b, and c, we are then able to calculate the lengths B and C:

by the law of sines, $\frac{A}{B} = \frac{\text{sine (a)}}{\text{sine (b)}}$

then $B = A\frac{\text{sine (b)}}{\text{sine (a)}}$ and $C = A\frac{\text{sine (c)}}{\text{sine (a)}}$

Triangulation

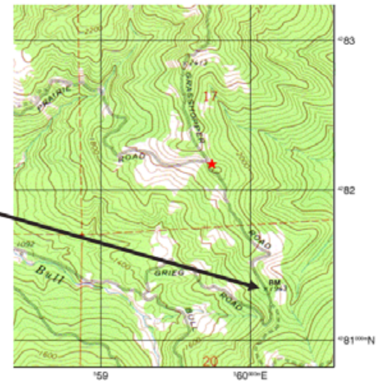


With the length C known, angles e, f, and g may then be measured. The law of sines may be used with the now known distance C to calculate lengths E and F. Successive datum points may be established to extend the network using primarily angle measurements.

Horizontal Survey Benchmarks

Benchmarks are monuments used to permanently mark geodetic surveys.

Benchmarks



Geodetic Surveys Evolved Through Time

1600s

1700s

1800s

Survey Network, 1900

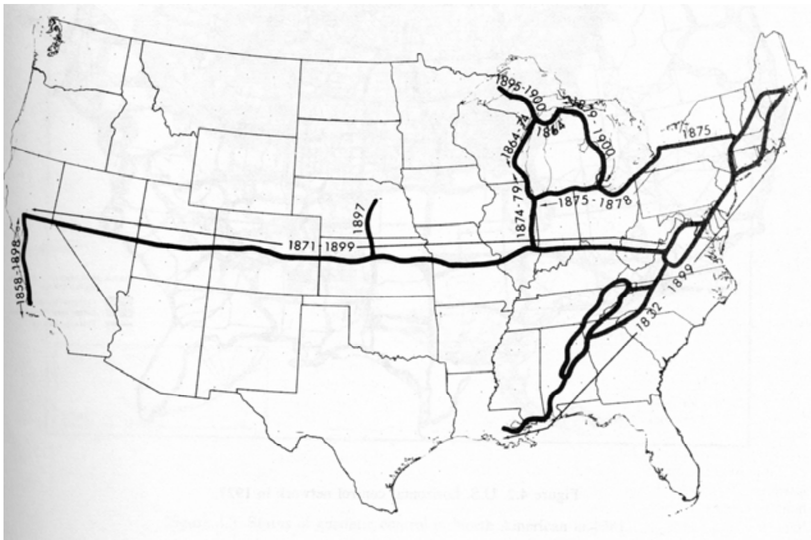


Figure 4.1. U.S. horizontal control network in 1900.

(from Schwartz, 1989)

North American Datum of 1927,
26,000 measured points, Clarke 1866 spheroid, fixed starting point in Kansas

NAD27 survey network

Survey Network,
1981

(from Schwartz, 1989)

Figure 4.3. Status of geodetic control in North American in 1981.

NAD83 successor to NAD27, involving approximately 250,000 measurement points in network, involving over 2 million distance measurements

NAD83 referenced to GRS80 ellipsoid, held no fixed stations

Datum "Adjustment"

A datum adjustment is a calculation of the coordinates of each benchmark – this is how we specify the "reference surface"

Errors in distance, angle measurements

Improvements in our measurements of Geoid, best spheroid

Improvements in computing capabilities

There are two horizontal control networks commonly referred to

North American Datum of 1927 (also NAD27)

North American Datum of 1983 (also NAD83*), to replace NAD27*

Two Main Classes of Datums

Pre-satellite: e.g., Clarke, Bessel, NAD27, NAD83(1986)
- large errors (10s to 100s of meters),
- local to continental

Post-satellite: e.g., NAD83(HARN), NAD83(CORS96), WGS84(1132), ITRF99
- small relative errors (cm to 1 m)
- global

Ellipsoid Estimates Continue to Evolve

- Based on satellite orbits – mass centered
- Better estimates of origin
- Very precise estimates of the location of tracking stations – and hence ellipsoid shape
- Differences small for most earth locations – a few centimeters (inches or less)

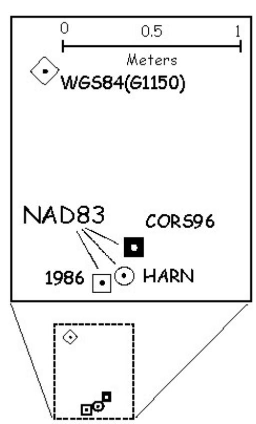
- The Continents are Moving

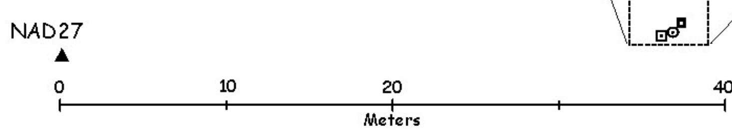
Our Estimate of Locations Change

Examples of Datum Shifts

New Jersey control point, successive datum transformations applied

Datum	Longitude (W)	Latitude(N)	Shift(m)
NAD27	74° 12' 3.86927"	40° 47' 0.76531"	
			36.3
NAD83(1986)	74° 12' 2.39240"	40° 47' 1.12726"	
			0.04
NAD83(HARN)	74° 12' 2.39069"	40° 47' 1.12762"	
			0.05
NAD83(CORS96)	74° 12' 2.39009"	40° 47' 1.12936"	
			0.95
WGS84(G1150)	74° 12' 2.39720"	40° 47' 1.15946"	





Vertical Datums

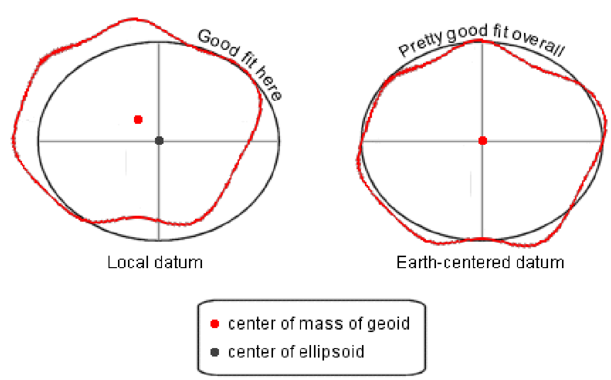
Like horizontal, but referenced to standard elevation and established using vertical leveling

Two major vertical datums,

North American Vertical Datum of 1927 (NAVD29), and an update,

North American Vertical Datum of 1988 (NAVD88)

Earth-centered datum and local datum

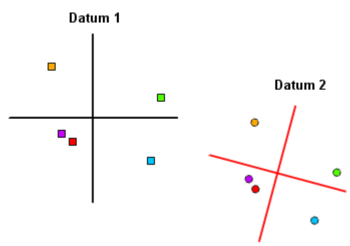


Which is better?

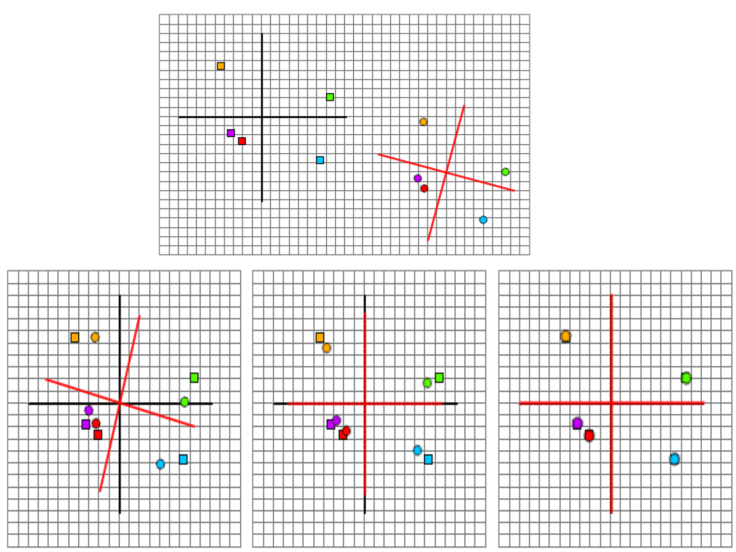
Transforming Between Reference Surfaces

We can transform positions from one ellipsoid to another via mathematical operations

e.g., an origin shift, rotation and scale

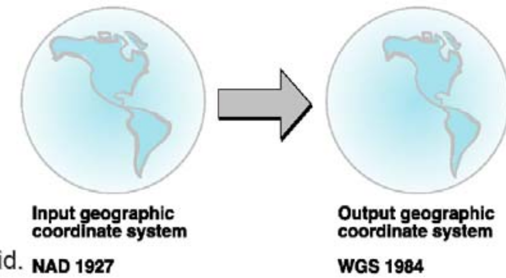


Transforming Between Reference Surfaces



Transforming Between Reference Surfaces

Because the geographic coordinate systems contain datums that are based on spheroids, a geographic transformation also changes the underlying spheroid.



A geographic transformation always converts geographic (longitude–latitude) coordinates.

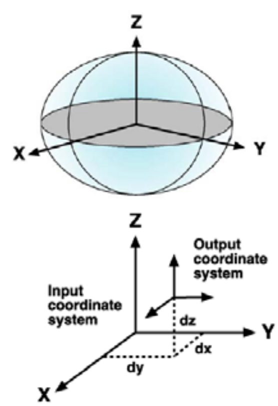
Some methods convert the geographic coordinates to geocentric (X, Y, Z) coordinates, transform the X, Y, Z coordinates, and convert the new values back to geographic coordinates.

Transforming Between Reference Surfaces

The simplest datum transformation method is a geocentric, or three-parameter, transformation.

The geocentric transformation models the differences between two datums in the X, Y, Z coordinate system.

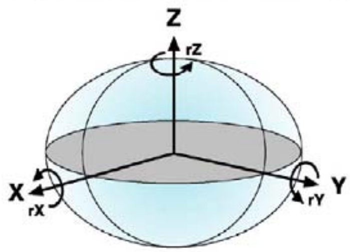
One datum is defined with its center at 0, 0, 0. The center of the other datum is defined at some distance (D X, D Y, D Z) in meters away.



$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{new} = \begin{bmatrix} \Delta X \\ \Delta Y \\ \Delta Z \end{bmatrix} + \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{original}$$

Transforming Between Reference Surfaces

A more complex and accurate datum transformation is possible by adding four more parameters to a geocentric transformation. The seven parameters are three linear shifts (D X, D Y, D Z), three angular rotations around each axis (rx , ry , rz), and a scale factor (s).



$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{new} = \begin{bmatrix} \Delta X \\ \Delta Y \\ \Delta Z \end{bmatrix} + (1+s) \cdot \begin{bmatrix} 1 & r_z & -r_y \\ -r_z & 1 & r_x \\ r_y & -r_x & 1 \end{bmatrix} \cdot \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{original}$$

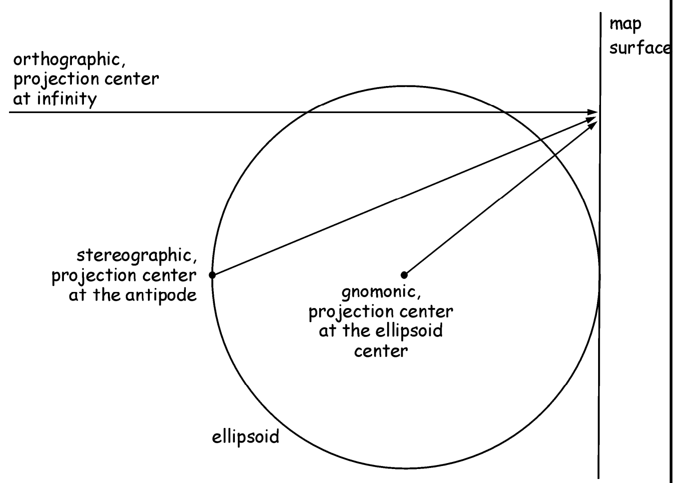
Summary

- The Earth's shape is approximated by an ellipsoid - the shape is better characterized by a geoid
- Horizontal positions defined relative to the ellipsoid
- Heights measured relative to the geoid
- Estimates of geoid changes through time
- A datum is a reference surface, a realization of the ellipsoid, against which locations are measured
- Multiple datums, improved through time

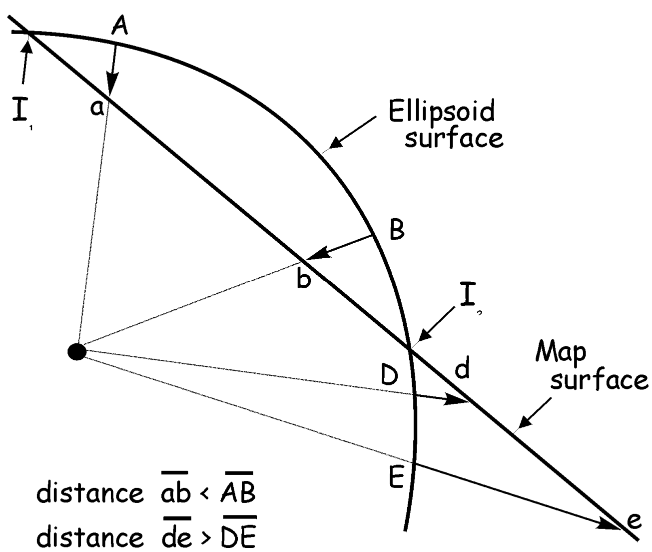
Map Projections

A systematic rendering

3-D spherical
to
2-D Cartesian system.



Distortion Varies Across Map



distance $\overline{ab} < \overline{AB}$

distance $\overline{de} > \overline{DE}$

Different map projections may distort the globe in different ways

•The projection surface

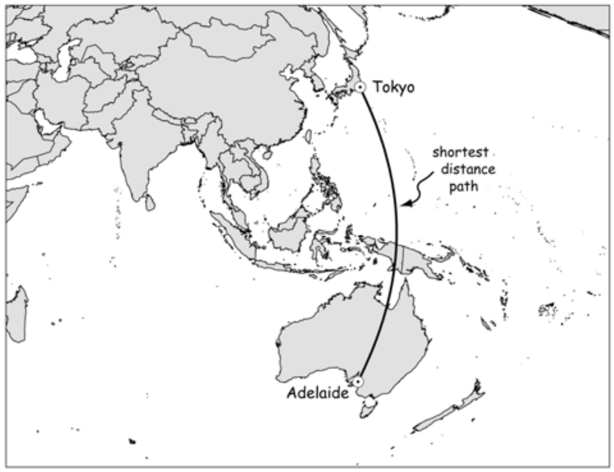
•Surface orientation

•The location of projection source

Distortion

- Shape
- Distance
- Direction
- Area

Straight line distortion

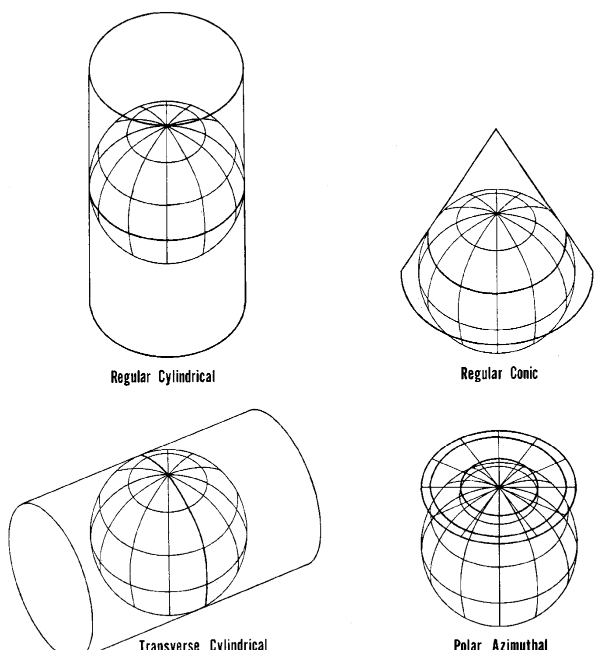


The projection surface:

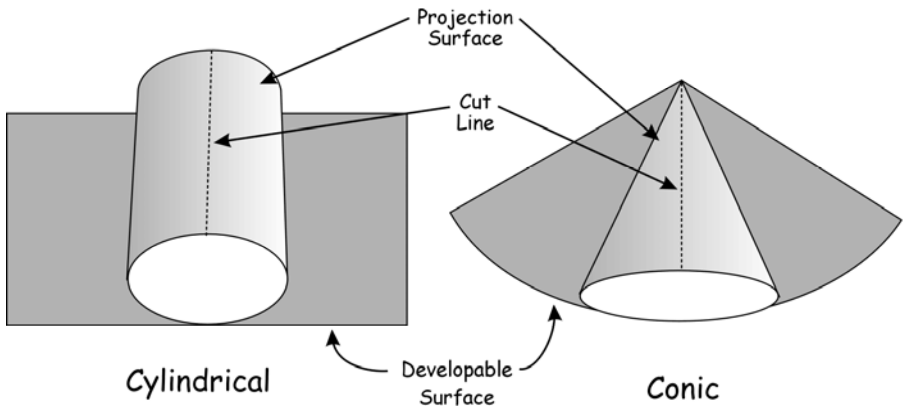
Cone – Conic

Cylinder - Cylindrical

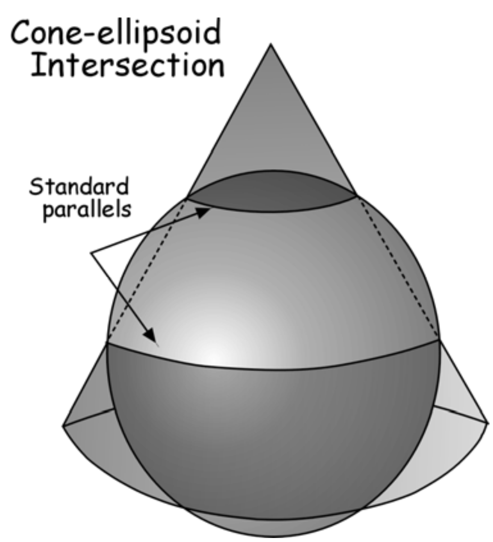
Plane - Azimuthul



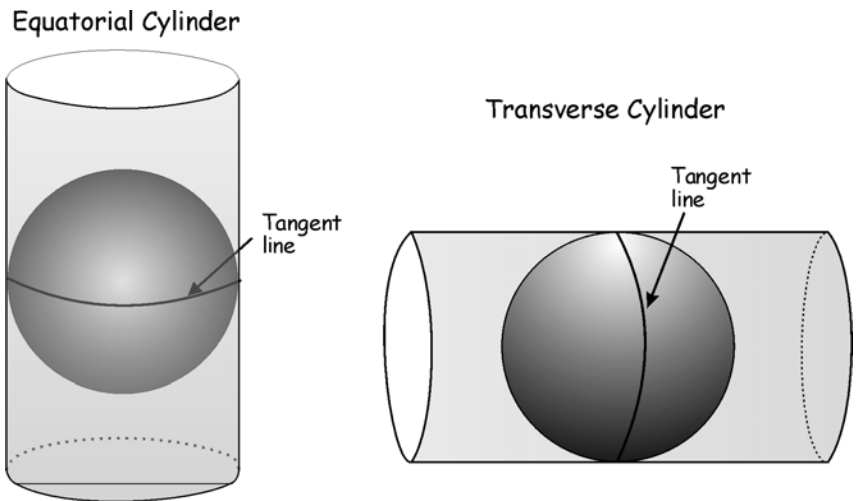
Projection Surfaces – "developable"



Developable Surface- Cone

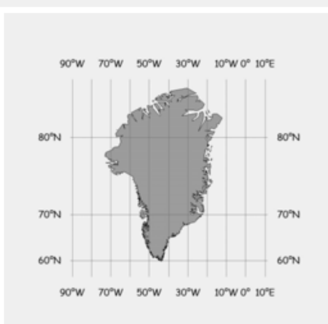


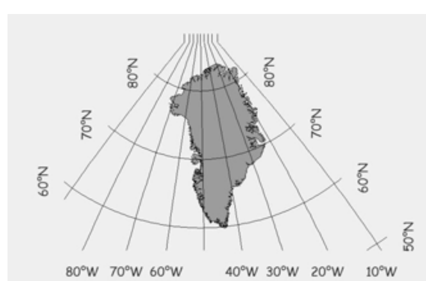
Developable Surface - Cylinder



Mathematical formulas

Projections are like political parties, they distort everything





Distortion properties:

preserve shape - *conformal (orthomorphic)*

preserve scale – equidistant

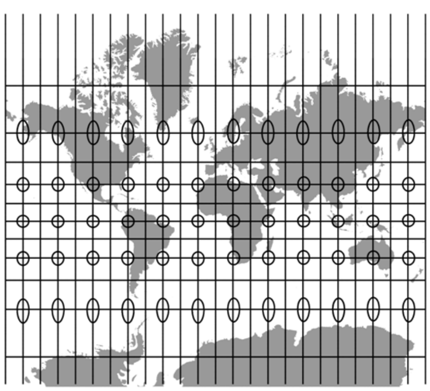
preserve direction – azimuthal

preserve great circles - gnomic

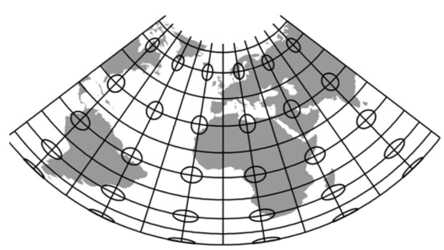
preserve circular shapes - stereographic

Distortion varies by developable surface

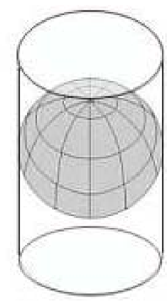
Cylindrical



Conic

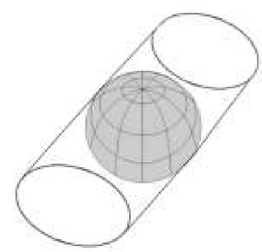


Projections Categorized by Orientation:



Equatorial - intersecting equator

Transverse - at right angle to equator



Specifying Projections

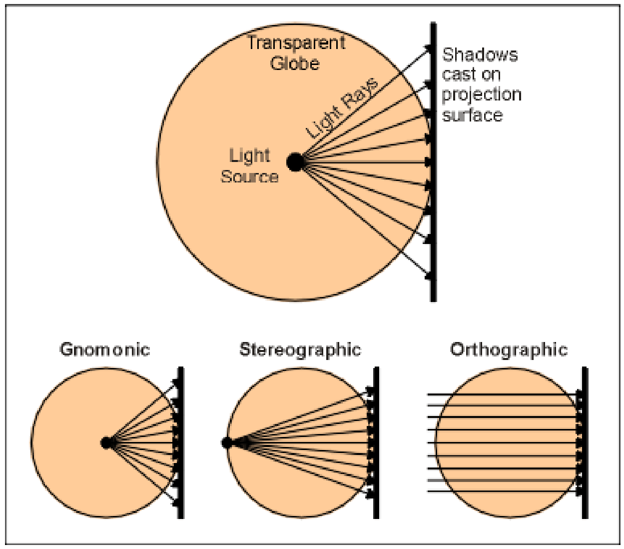
- The type of developable surface (e.g., cone)
- The size/shape of the Earth (ellipsoid, datum), and size of the surface
- Where the surface intersects the ellipsoid
- The location of the map projection origin on the surface, and the coordinate system units

Categorized by the Location of Projection Source

Gnomonic - center of globe

Stereographic - at the antipode

Orthographic - at infinity



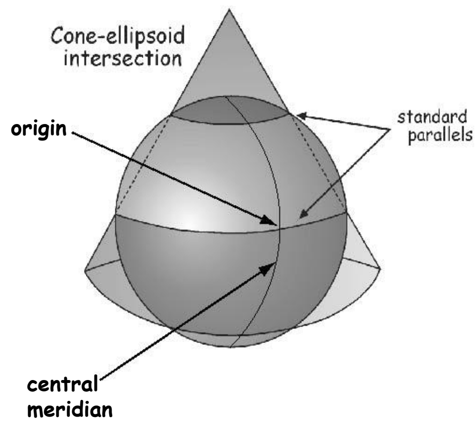
Source:http://www.fes.uwaterloo.ca/crs/geog165/mapproj.htm

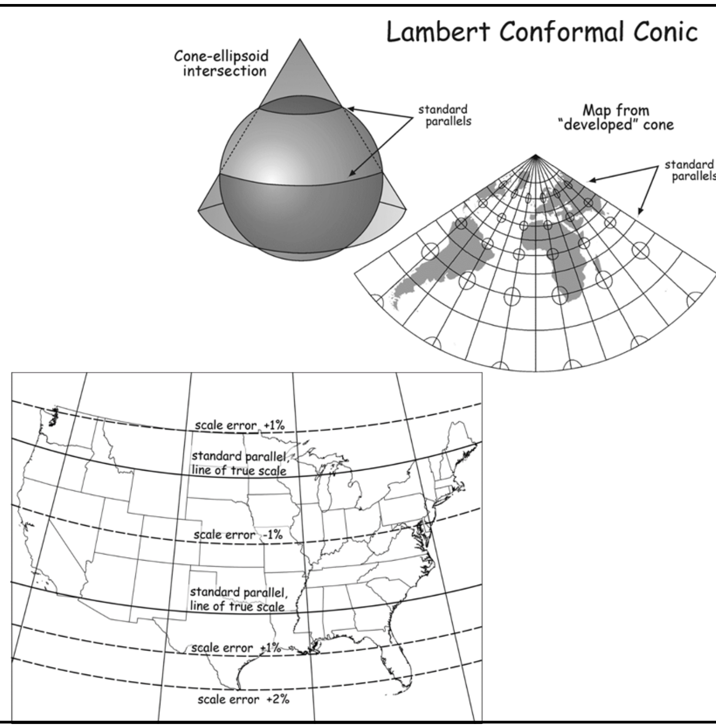
"Standard" Projections

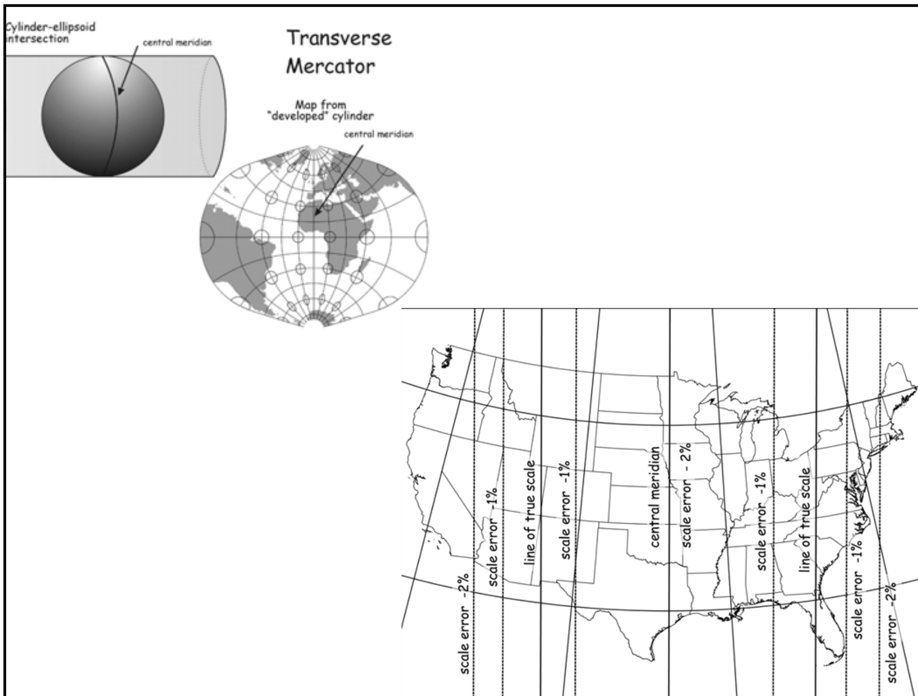
- Governments (and other organizations) define "standard" projections to use
- Projections preserve specific geometric properties, over a limited area
- Imposes uniformity, facilitates data exchange, provides quality control, establishes limits on geometric distortion.

Defining a Projection – LCC (Lambert Conformal Conic)

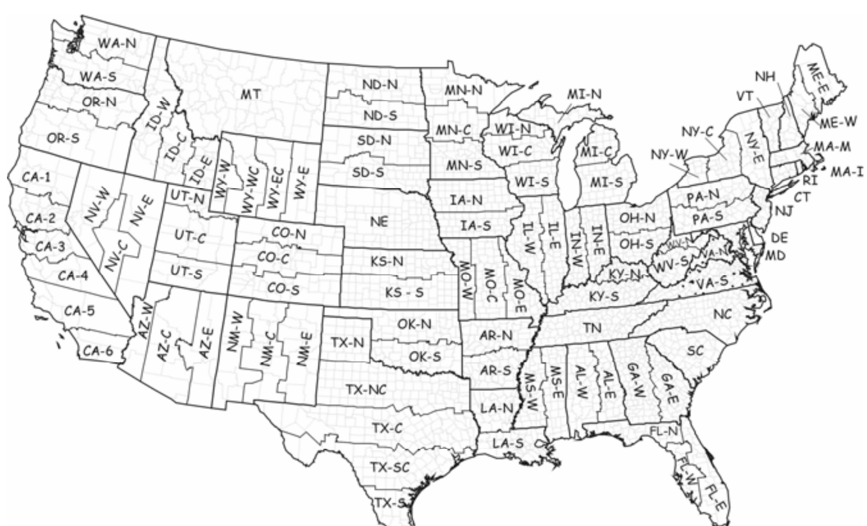
- The LCC requires we specify an upper and lower parallel
- A spheroid
- A central meridian
- A projection origin





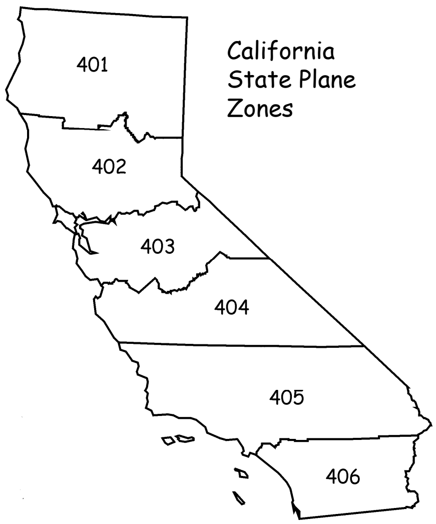


State Plane Coordinate System Zones



MISSISSIPPI EAST ZONE FIPS ZONE: 2301
MISSISSIPPI WEST ZONE FIPS ZONE: 2302

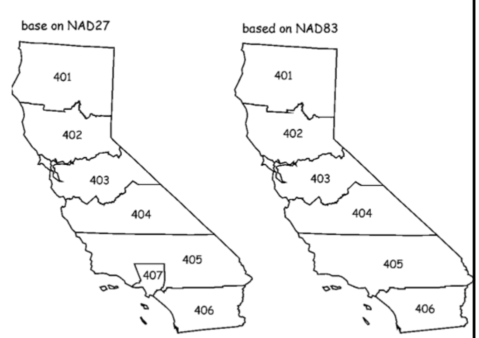
State Plane Coordinate System



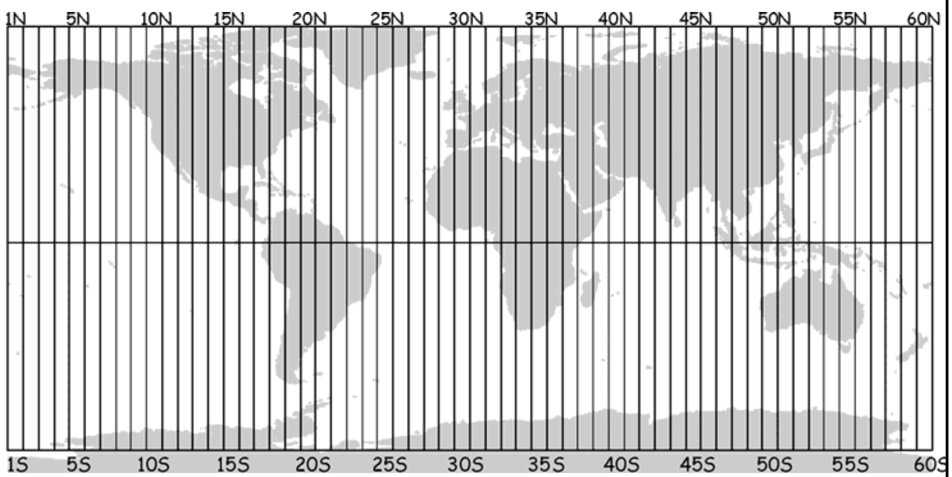
- Each state partitioned into zones
- Each zone has a different projection specified
- Distortion in surface measurement less than 1 part in 10,000 within a zone

State Plane Coordinate Systems

- Uses Lambert conformal conic (LCC) and Transverse Mercator (TM, cylindrical)
- LCC when long dimension East-West (31 states)
- TM when long dimension N-S (22 states)
- May be mixed, as many zones used as needed
- Political boundaries
- More than one version



Universal Transverse Mercator – UTM System



UTM Zone Details

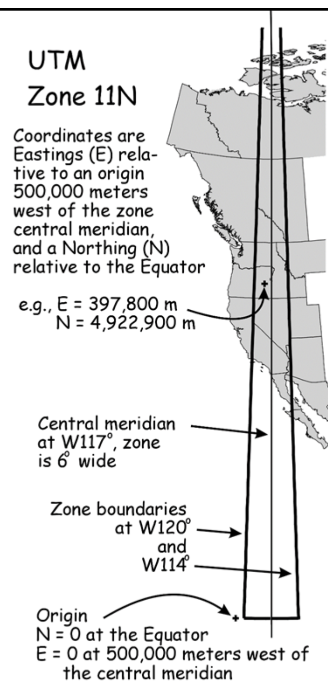
Each Zone is 6 degrees wide

Zone location defined by a central meridian

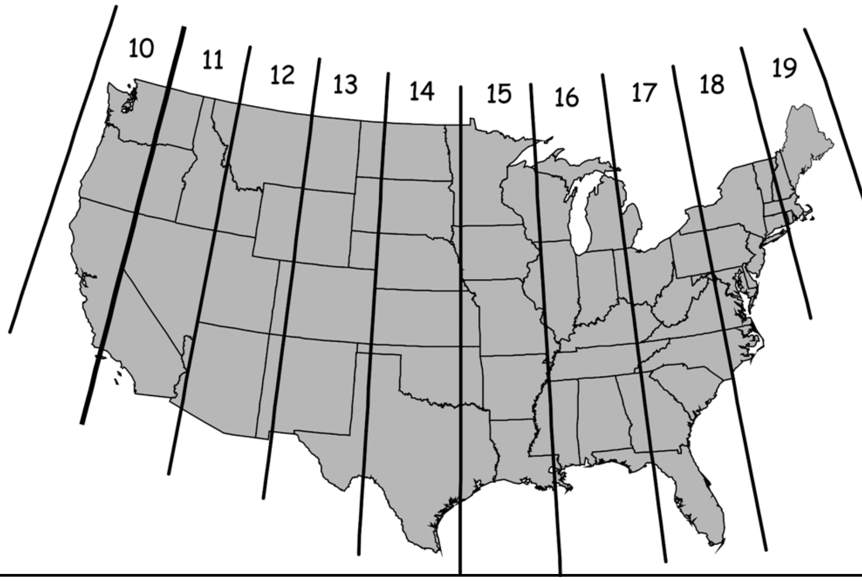
Origin at the Equator, 500,000m west of the zone central Meridian

Coordinates are always positive (offset for south Zones)

Coordinates discontinuous across zone boundaries



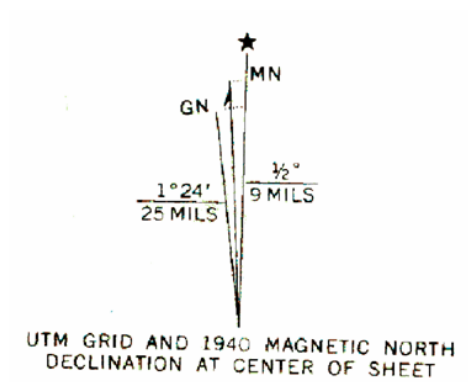
Universal Transverse Mercator Projection – UTM Zones for the U.S.



UTM

Measurements of distance, shape & area with .04% or less distortion.*

Grid allows a slight tilt from True North. “UTM grid declination”*



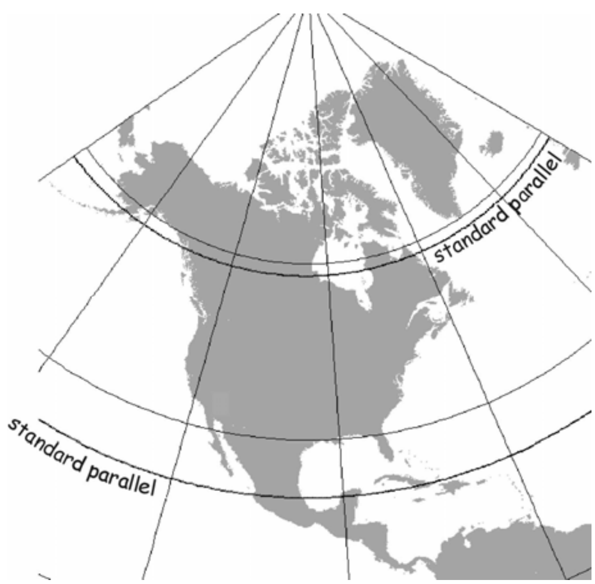
From USGS 1:24k map sheet

Coordinate Systems Notation

Latitude/Longitude

Degrees Minutes Seconds	45° **3' 38" N**
Degrees Minutes (decimal)	45° 3.6363' N
Degrees (decimal)	45.0606° N
State Plane (feet)	2,951,384.24 N
UTM (meters)	4,996,473.72 N

National Projections



Map Projections vs. Datum Transformations

- A map projections is a systematic rendering from 3-D to 2-D
- Datum transformations are from one datum to another, 3-D to 3-D
- Changing from one projection to another may require both

Simple Projection: Example

Conversion from geographic (lon, lat) to projected coordinates

Given longitude = λ latitude = ϕ

Mercator projection coordinates are:

$x = R \cdot (\lambda - \lambda_o)$
$y = R \cdot \ln(\tan(90^o + \phi)/2)$

where R is the radius of the sphere at map scale (e.g., Earth's radius), ln is the natural log function, and λ_o is the longitudinal origin (Greenwich meridian)

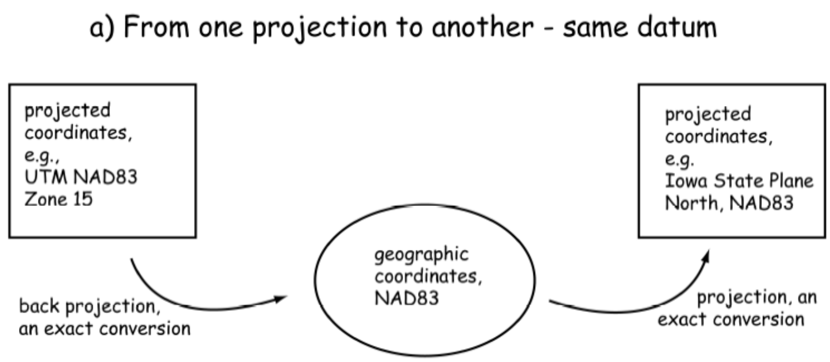
Example:

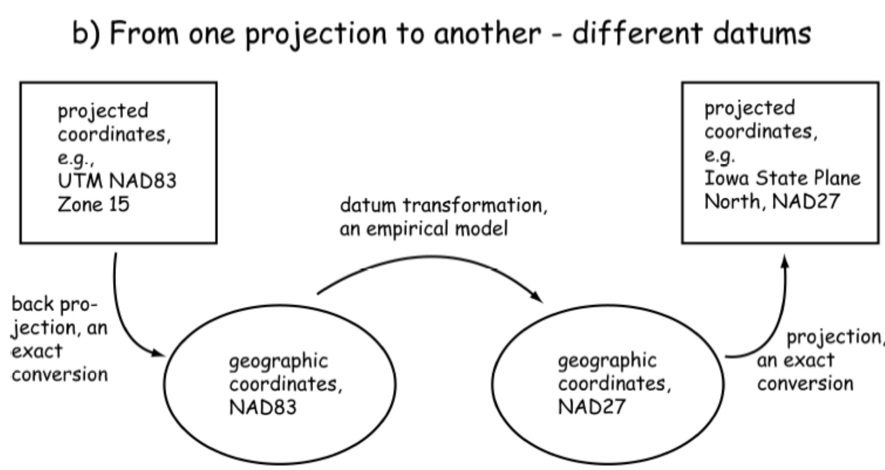
$\lambda = 30$, $\phi = 45$

X = R (30*π/180- 0)
= 6,378 (1.7320)
= 11,047

Y = R ln(tan(45+45/2))
= 6,378 ln(1.73205)
= 6,378 * 0.5493
= 3,503

From one Projection to Another





Map Projections Summary

- Projections specify a two-dimensional coordinate system from a 3-D globe
- All projections cause some distortion
- Errors are controlled by choosing the proper projection type, limiting the area applied
- There are standard projections
- Projections differ by datum – know your parameters

Coordinate Systems

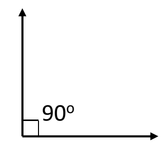
Pairs or triplets of numbers to specify location

We must define
- An origin (may be point or surface)
- Standard directions

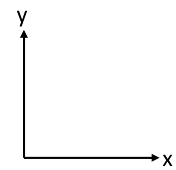
Cartesian coordinates (right angle)

Spherical coordinates (geographic or geodetic)

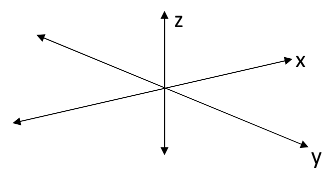
Cartesian Coordinates
(right angle)



Generally, location is defined in two dimensions, X and Y, or in three dimensions, the X, Y, and Z



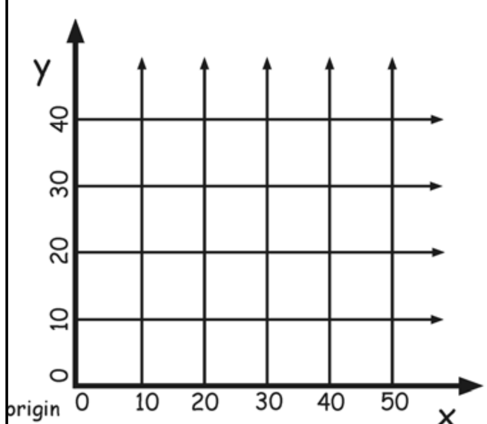
Two-dimensional system most often used with
Projected coordinates



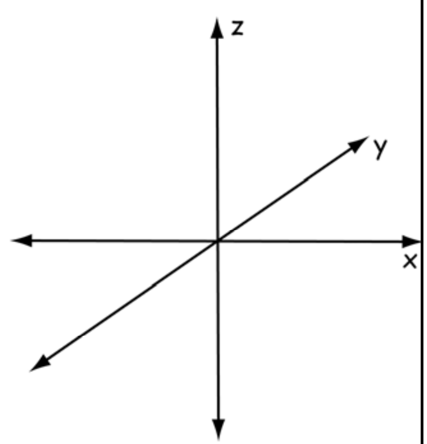
Three dimensional system used with
Geocentric coordinates

Cartesian Coordinates

2 - Dimensional



3 - Dimensional



Spherical Coordinates

- Use angles of rotation to define a directional vector
- Use the length of a vector originating near the ellipsoid center to define the location on the surface