UNDERSTANDING COORDINATE SYSTEMS AND MAP PROJECTIONS

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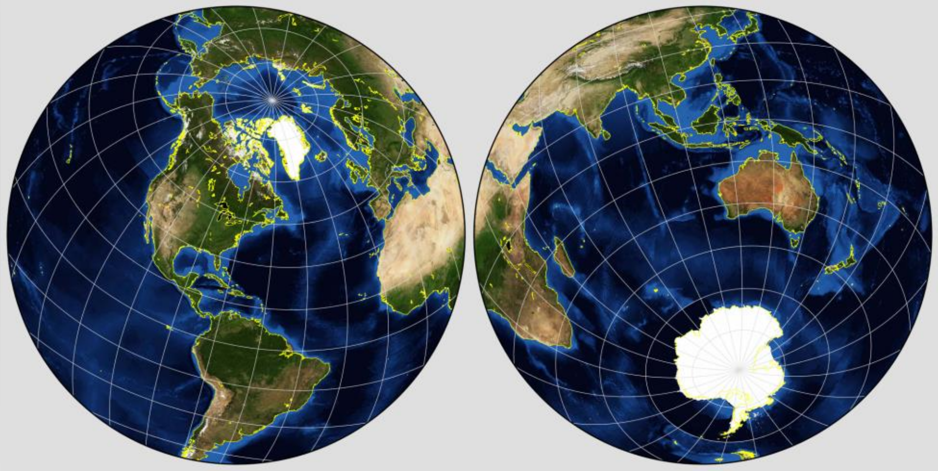
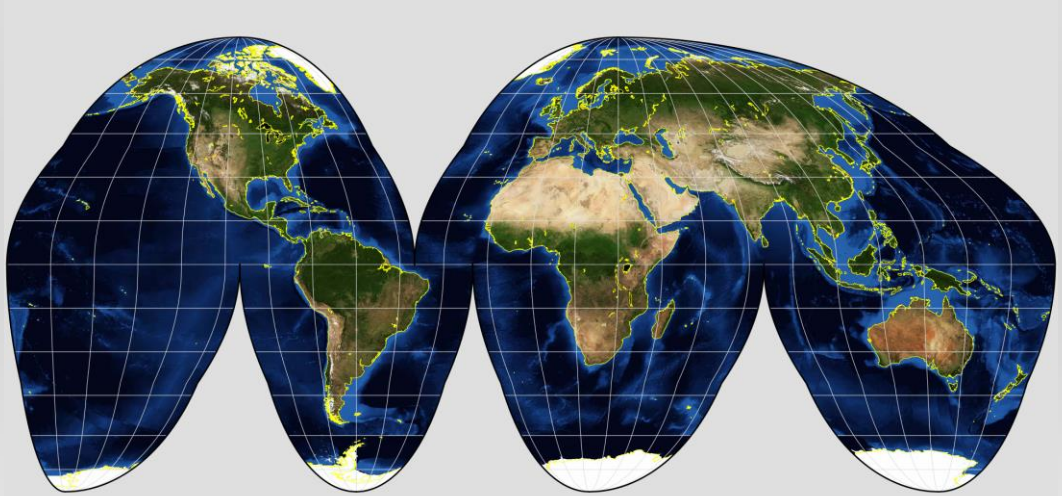
LEARNING OUTCOMES

- Define the terms:
  - PCS
  - GCS
  - Projection method
- Select the appropriate projection system based on a region of interest
- Correctly project data sets to a new spatial reference system when needed.
- Demonstrate an understanding that no matter how we project spherical data (3D) onto a plane (2D), **there will be distortion**.

WHY DO YOU NEED TO KNOW THIS?

- Spatial data – related to certain location
- Globes are great for visualisation purposes, they are not practical for many uses, one reason being that they are not very portable
- A round Earth **does not fit without distortion** on a flat piece of paper





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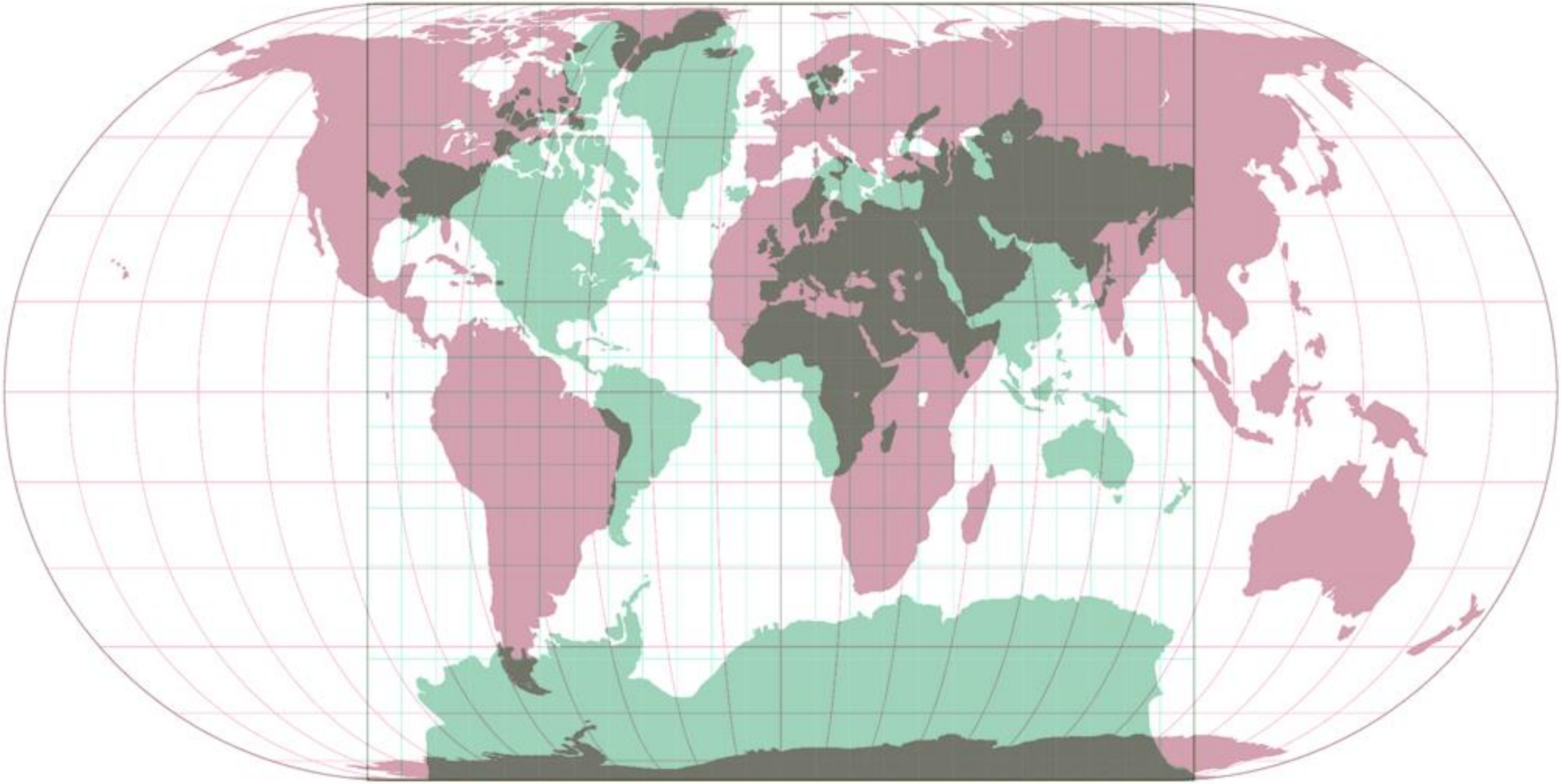


SPATIAL REFERENCE SYSTEM (SRS) OR COORDINATE REFERENCE SYSTEM (CRS)

- Spatial Reference Systems, also referred to as Coordinate Systems, include two common types:
  - ✓ Geographic Coordinate Sytems (GCS)
  - ✓ Projected Coordinate Systems (PCS)
- A **Spatial Reference System Identifier** (**SRID**) is a unique value used to unambiguously identify projected, unprojected, and local spatial coordinate system definitions. These coordinate systems form the heart of all GIS applications. (wiki)

SPATIAL REFERENCE SYSTEM IDENTIFIER (SRID)

- Virtually all major spatial vendors have created their own SRID implementation or refer to those of an authority, such as the European Petroleum Survey Group (EPSG).
- In spatially enabled databases (such as MySQL, PostGIS), SRIDs are used to uniquely identify the coordinate systems used to define columns of spatial data or individual spatial objects in a spatial column.
- SRIDs are typically associated with a well-known text (WKT) string definition of the coordinate system. A WKT string for a spatial reference system describes the datum, geoid, coordinate system, and map projection (in case of projected coordinate system) of the spatial objects.

WKT FOR WGS84 — SRID 4326

```
GEOGCS["WGS 84",
    DATUM["WGS_1984",
        SPHEROID["WGS 84",6378137,298.257223563,
            AUTHORITY["EPSG","7030"]],
        AUTHORITY["EPSG","6326"]],
    PRIMEM["Greenwich",0,
        AUTHORITY["EPSG","8901"]],
    UNIT["degree",0.0174532925199433 28,
        AUTHORITY["EPSG","9122"]],
    AUTHORITY["EPSG","4326"]]
```

GEOGRAPHIC COORDINATE SYSTEMS (GCS)

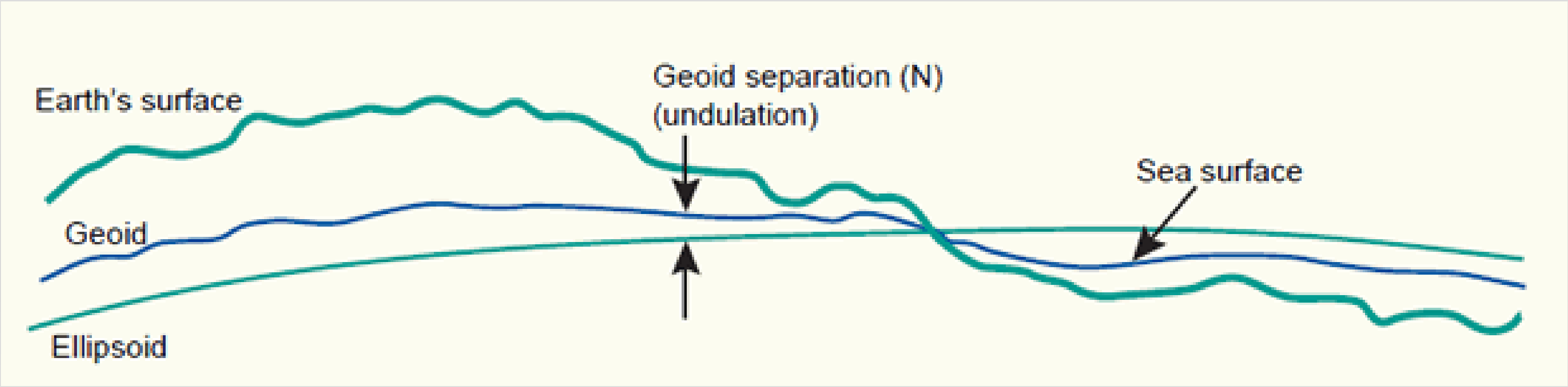
- A geographic coordinate system (GCS) uses an ellipsoidal surface to define locations on the Earth. There are three parts to a geographic coordinate system:
    - ✓ **A datum** - an ellipsoidal (spheroid) model of the Earth to use. Common datums include WGS84 (used in GPS).
    - ✓ **A prime meridian**
    - ✓ **Angular unit of measure**

GEODETIC DATUM

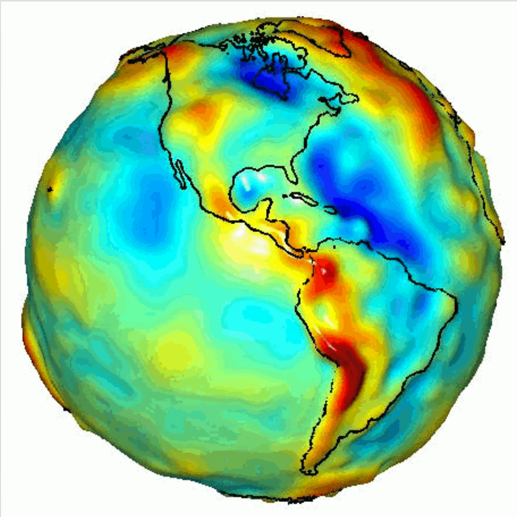
- Horizontal datum - used for describing a point on the Earth's surface, in latitude and longitude or another coordinate system.
- Vertical datum - measure elevations or depths.

HORIZONTAL DATUM I

- The **geoid** is defined as the surface of the earth's gravity field, which is approximately the same as mean sea level. It is perpendicular to the direction of gravity pull. Since the mass of the earth is not uniform at all points, and the direction of gravity changes, the shape of the geoid is irregular.
- To simplify the model, various spheroids or **ellipsoids** have been devised.



Source: [MapToasterTopo]



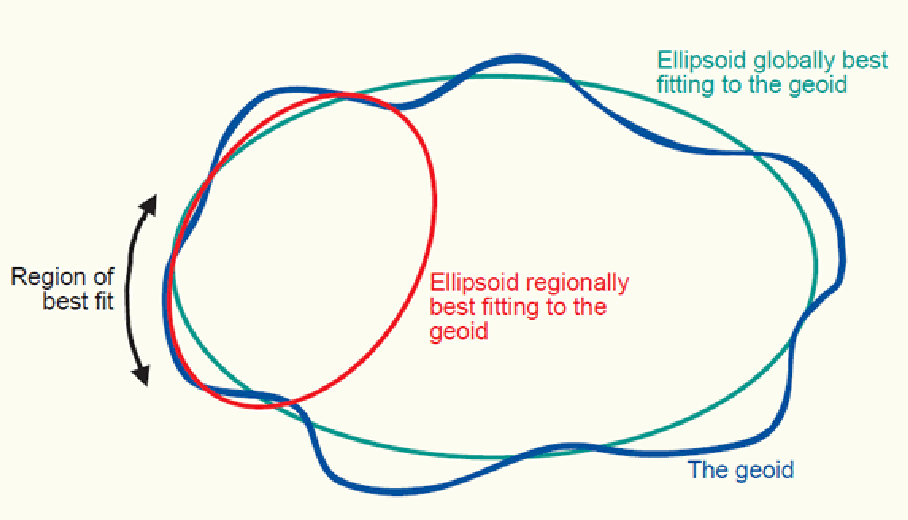
Source: NASA GRACE gravity model

HORIZONTAL DATUM II

- A **datum** is a model of the earth that is used in mapping. The datum consists of **a set of parameters that define the shape and size of the ellipsoid and it's orientation in space**. A datum is chosen to give the best possible fit to the true shape of the Earth.
- Latitude and longitude are commonly used to refer to a specific location on the surface of the Earth. It is important to keep in mind that latitude and longitude are always specified in terms of a datum. **The latitude and longitude of your current position are different for different datums.**
- If you are working with latitude/longitude coordinates and you get an error of a couple of hundred metres, you most likely are using the wrong datum.

HORIZONTAL DATUM III

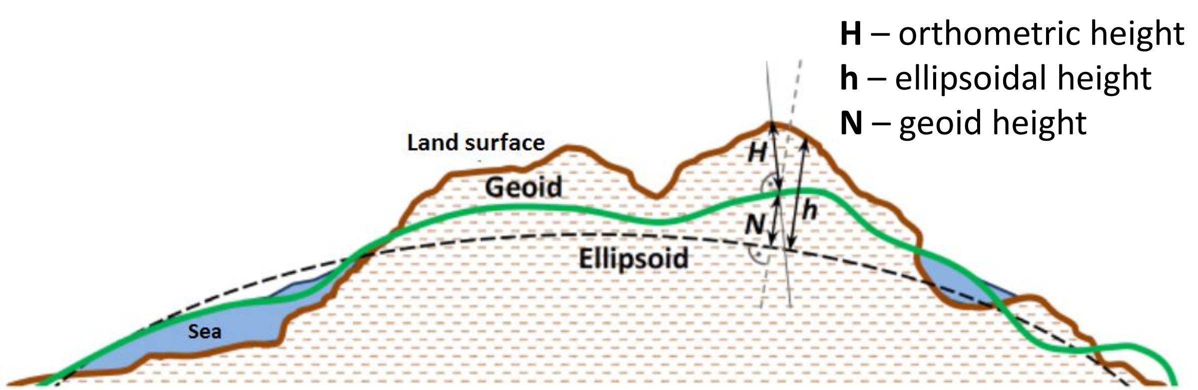
- Several standard datums have been adopted for regional or national maps. Many of them are optimised for use in one particular part of the world. Familiar to GPS users, is the **WGS-84 datum**. WGS-84 is an example of a datum that is used globally. Global datums may not fit any particular area as well as a local one.
- Datums are not static, and often see updates and adjustments throughout time. Therefore, it is very important that you read the documentation of the datasets that you using in your GIS to determine exactly which datum was used to determine locations.



Source: [MapToasterTopo]

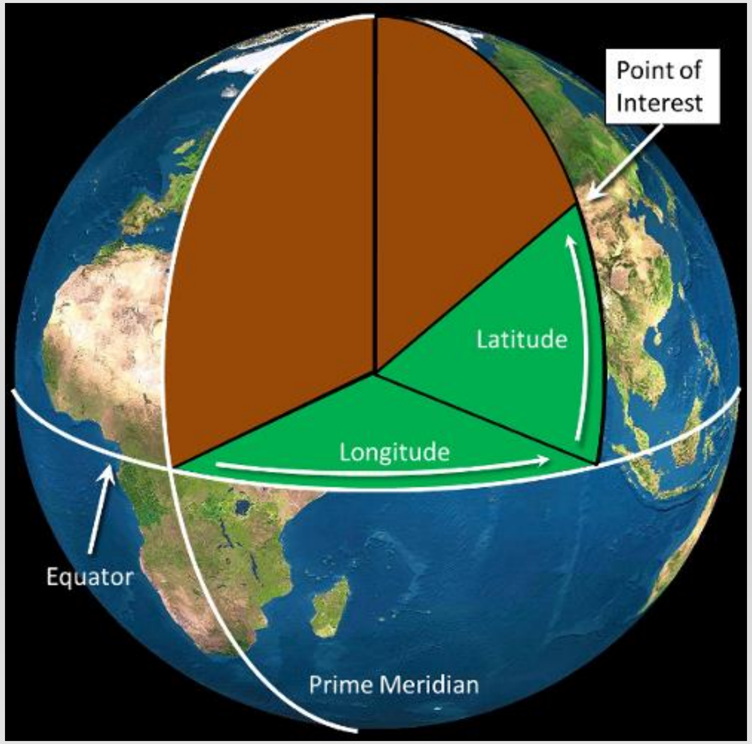
VERTICAL DATUM

- A vertical datum is a reference surface of zero elevation to which heights are referred to.
- Vertical datums are either: tidal, based on sea levels; gravimetric, based on a geoid; or geodetic, based on the same ellipsoid models of the Earth used for computing horizontal datums
- Estonia recently switched from Baltic Height System to European Vertical Reference System which meant a 15 to 24-centimeter increase of absolute heights depending on the area
- WGS 84 is ellipsoid-based datum



GEOGRAPHIC COORDINATES

- Location on an **ellipsoid** is defined by **latitude and longitude (geographic coordinates)** that specifies the **angle** between any point and the equator, and the **angle** between any point and the prime meridian.



Geographic coordinates: latitude and longitude

Example: Tartu
58° 23′ N, 26° 43′ E

Source: [Humboldt State Geospatial Online]()

GEOGRAPHIC COORDINATES

- Both latitude and longitude are typically represented in two ways:
  - ✓ Degrees, Minutes, Seconds (DMS), for example, 58° 23′ 12′ ′N, 26° 43′ 21′ ′E
  - ✓ Decimal Degrees (DD) used by computers and stored as float data type, for example, 58.38667 and 26.7225

Convert 126° 12′ 27″ into decimal degree form.

$$
\begin{aligned}
126^\circ\, 12'\, 27'' &= 126^\circ + 12' + 27'' \\
&= 126^\circ + 12'\left(\frac{1^\circ}{60'}\right) + 27''\left(\frac{1^\circ}{3600''}\right) \\
&= 126^\circ + 0.2^\circ + 0.0075^\circ \\
&= \boxed{126.2075^\circ}
\end{aligned}
$$

DECIMAL DEGREES

- **Decimal degrees** (DD)Express latitude and longitude geographic coordinates as decimal fractions
- The equator is divided into 360 degrees of longitude, so each degree at the equator represents approximately 111.32 km. As one moves away from the equator towards a pole, one degree of longitude is decreasing with the distance, approaching zero at the pole

Degree precision versus length

decimal places	decimal degrees	DMS	qualitative scale that can be identified	N/S or E/W at equator	E/W at 23N/S	E/W at 45N/S	E/W at 67N/S
0	1.0	1° 00′ 0″	country or large region	111.32 km	102.47 km	78.71 km	43.496 km
1	0.1	0° 06′ 0″	large city or district	11.132 km	10.247 km	7.871 km	4.3496 km
2	0.01	0° 00′ 36″	town or village	1.1132 km	1.0247 km	787.1 m	434.96 m
3	0.001	0° 00′ 3.6″	neighborhood, street	111.32 m	102.47 m	78.71 m	43.496 m
4	0.0001	0° 00′ 0.36″	individual street, land parcel	11.132 m	10.247 m	7.871 m	4.3496 m

Source: Wiki

HOW TO CHOOSE PRECISION?

WHAT THE NUMBER OF DIGITS IN YOUR COORDINATES MEANS

LAT/LON PRECISION	MEANING
28°N, 80°W	YOU'RE PROBABLY DOING SOMETHING SPACE-RELATED
28.5°N, 80.6°W	YOU'RE POINTING OUT A SPECIFIC CITY
28.52°N, 80.68°W	YOU'RE POINTING OUT A NEIGHBORHOOD
28.523°N, 80.683°W	YOU'RE POINTING OUT A SPECIFIC SUBURBAN CUL-DE-SAC
28.5234°N, 80.6830°W	YOU'RE POINTING TO A PARTICULAR CORNER OF A HOUSE
28.52345°N, 80.68309°W	YOU'RE POINTING TO A SPECIFIC PERSON IN A ROOM, BUT SINCE YOU DIDN'T INCLUDE DATUM INFORMATION, WE CAN'T TELL WHO
28.5234571°N, 80.6830941°W	YOU'RE POINTING TO WALDO ON A PAGE
28.523457182°N, 80.683094159°W	"HEY, CHECK OUT THIS SPECIFIC SAND GRAIN!"
28.523457182818284°N, 80.683094159265358°W	EITHER YOU'RE HANDING OUT RAW FLOATING POINT VARIABLES, OR YOU'VE BUILT A DATABASE TO TRACK INDIVIDUAL ATOMS. IN EITHER CASE, PLEASE STOP.

Source: PhD Comic

MOST COMMON GEOGRAPHIC COORDINATE SYSTEM – WGS84

- WGS84 (EPSG: 4326) is the most common spatial reference for storing a referencing data across the entire world. It serves as the default for both the PostGIS spatial database and the GeoJSON standard. It is also used by default in most web mapping libraries.
- Because of its use in GPS, 4326 is generally assumed to be the spatial reference when talking about "latitude" or "longitude".

WGS84 is not a projection!

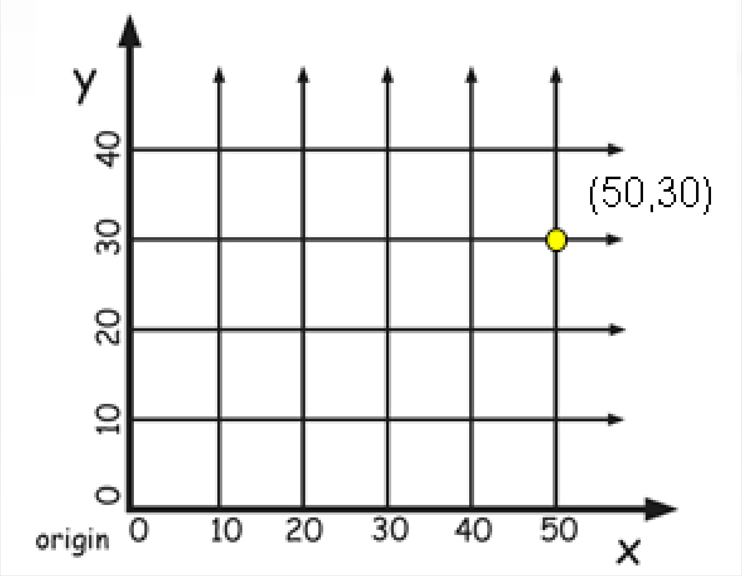
Source: ESRI

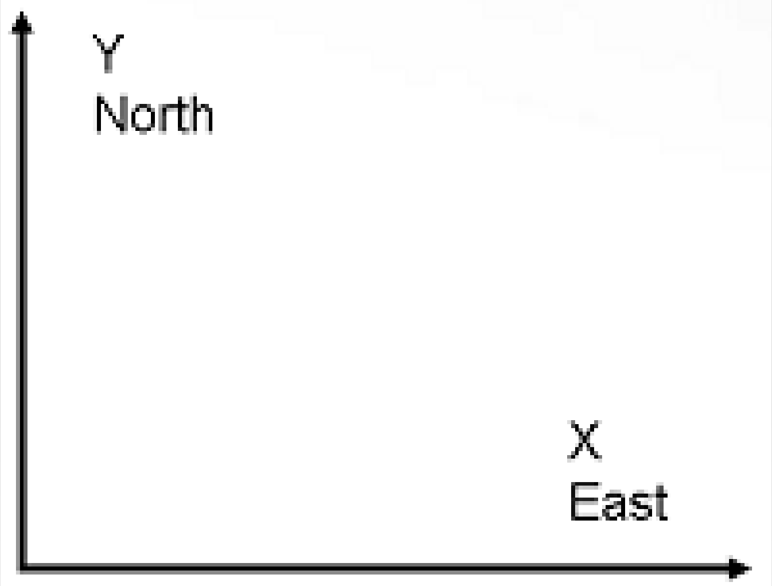
PROJECTED COORDINATE SYSTEMS (PCS) I

- Projected coordinate systems define a flat 2D Cartesian surface. Unlike a geographic coordinate system, a projected coordinate system has constant lengths, angles, and areas across the two dimensions. A projected coordinate system **is always based on a geographic coordinate system** that references a specific datum.
- Projected Coordinate Systems consist of:
  - **Geographic Coordinate System**
  - **Projection Method**
  - **Projection Parameters (standard points and lines, Latitude of Origin, Longitude of Origin, False Easting, False Northing etc)**
  - **Linear units (meters, kilometers, miles etc)**

PROJECTED COORDINATE SYSTEMS (PCS) II

- Location is defined on a **flat** surface using **Cartesian** coordinates (i.e., x and y, and z) that specify **horizontal and vertical** position.
- In GIS, we use X and Y but also "Easting" for X and "Northing" for Y.



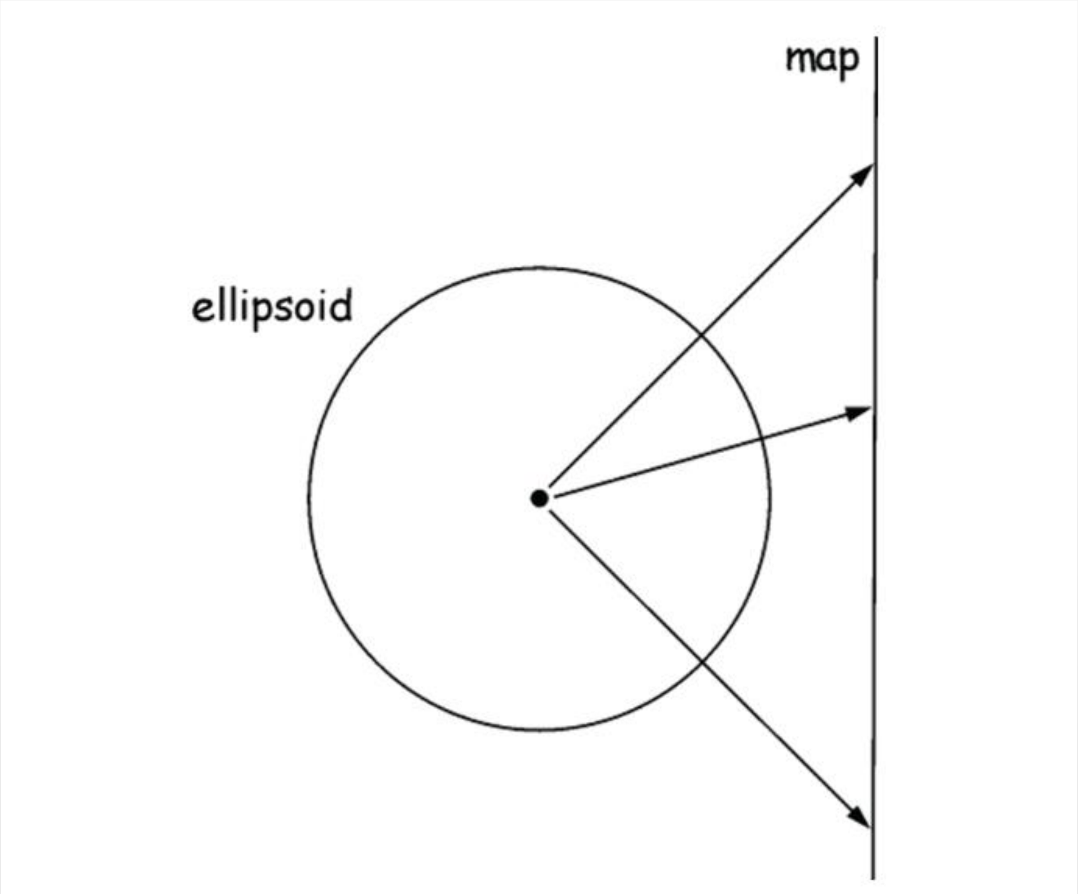


All projected coordinate systems are based on a GCS (geographic coordinate system)

Source: [Humboldt State Geospatial Online]

PROJECTING

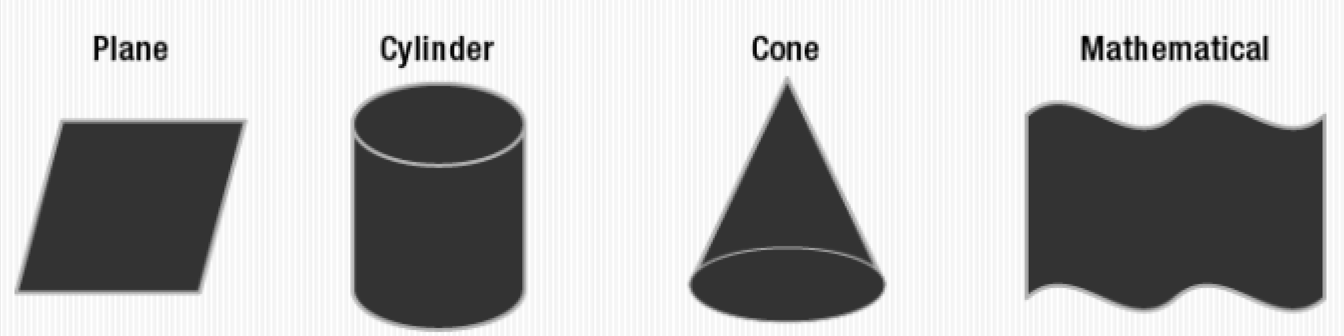
- The earth is an ellipsoid. To view spatial data on paper and computer screens, we need to project the data onto a 2D surface. This is called "**projecting**".
- **A map projection** is defined as a systematic rendering of locations from the curved earth surface onto a flat map surface.



Source: [Humboldt State Geospatial Online]

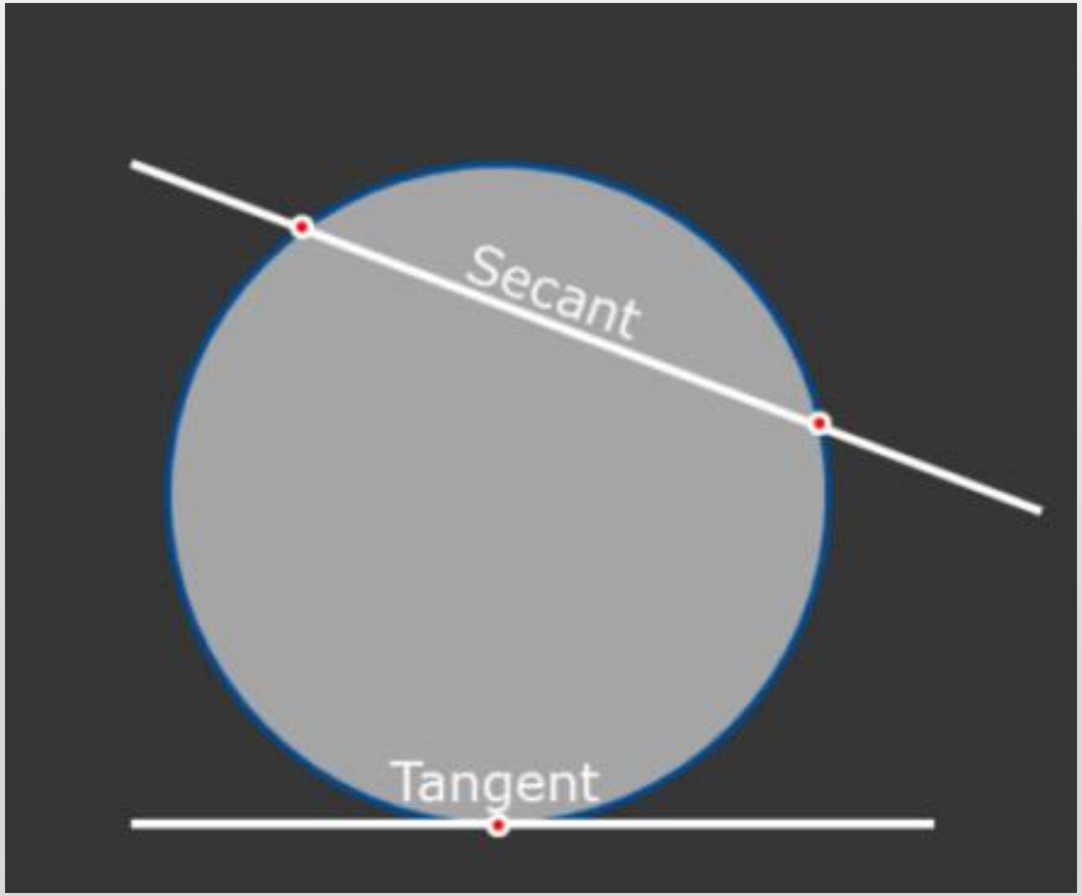
DEVELOPABLE SURFACE

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

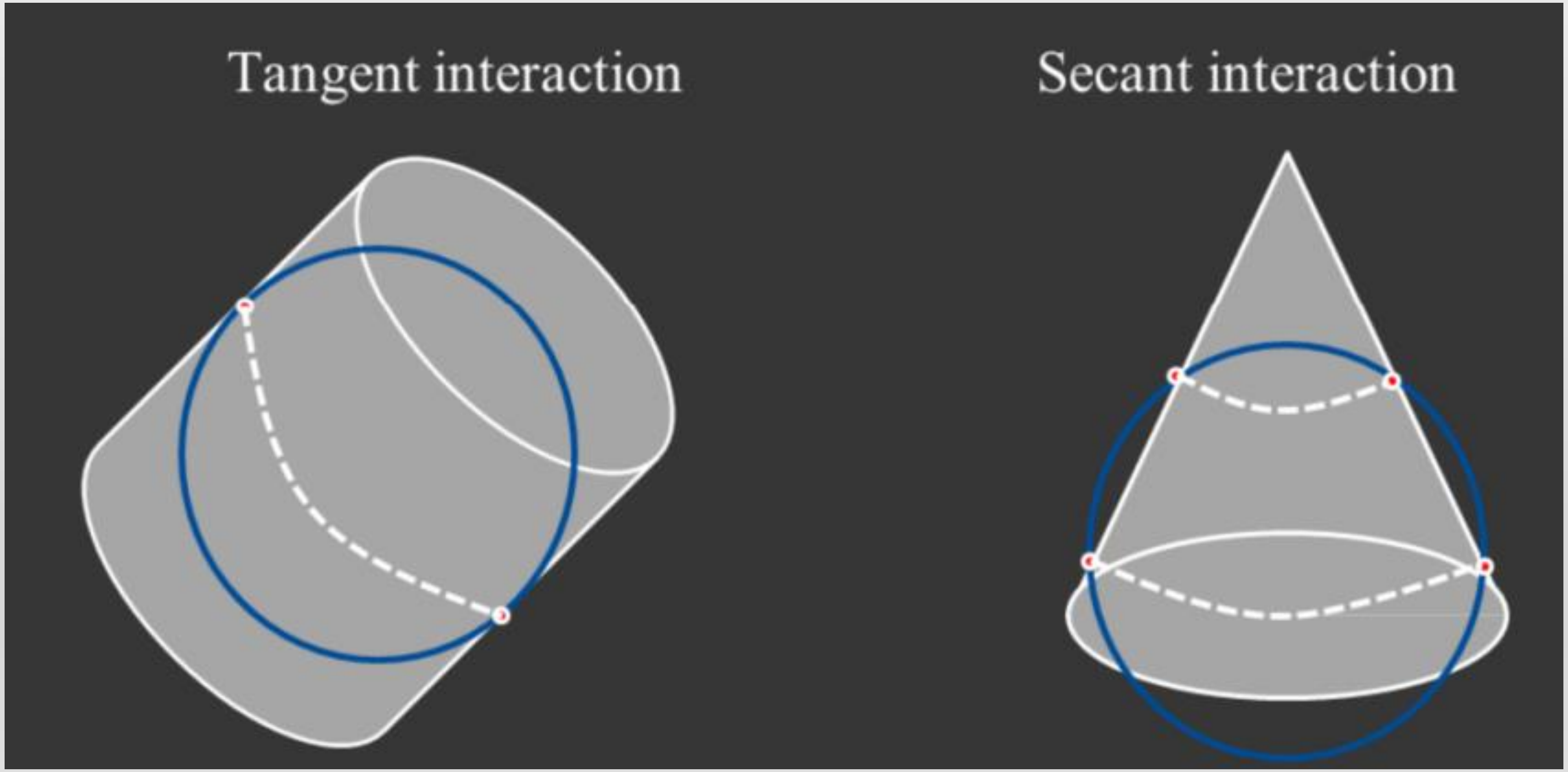


Developable surfaces touch the spheroid/ellipsoid in either:

- Two points - secant line
- One point - tangent line



- Interaction between developable surfaces and spheroid/ellipsoid

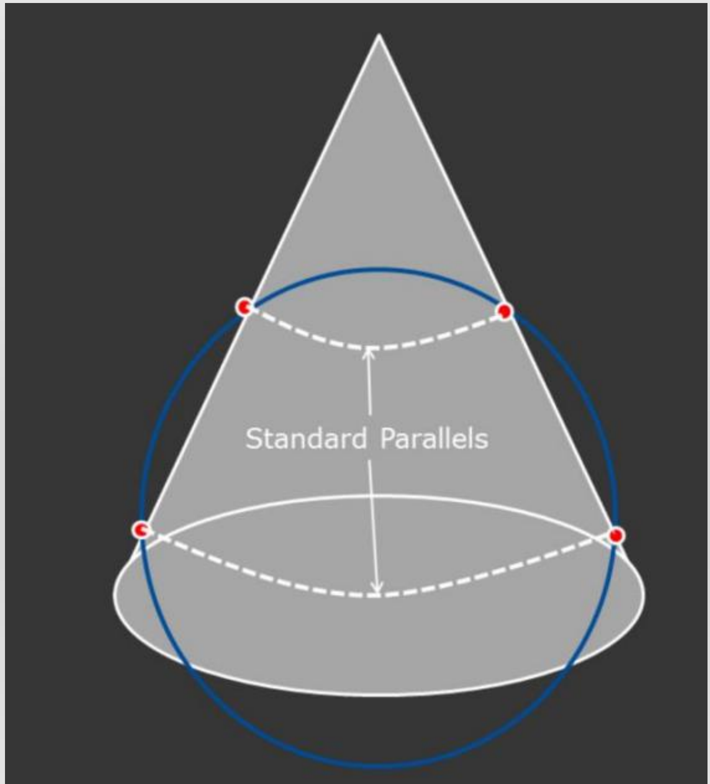


PROJECTION PARAMETERS

- standard points and lines
- projection aspect
- central meridian and parallel
- latitude of origin, longitude of origin
- false northing and easting
- light source location

STANDARD POINTS AND LINES

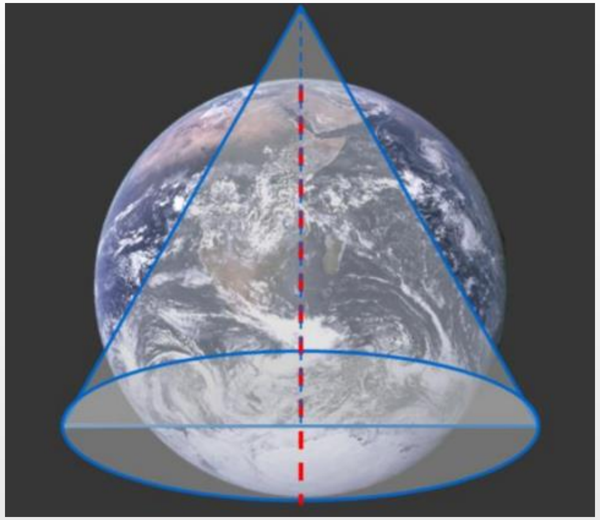
- **Definition:** a point or line of intersection between the developable surface and the spheroid or ellipsoid.
- Standard lines:
  - ✓ If standard line falls on a line of latitude, it is known as a **standard parallel**
  - ✓ If standard line falls on a line of longitude, it is known as a **standard meridian**



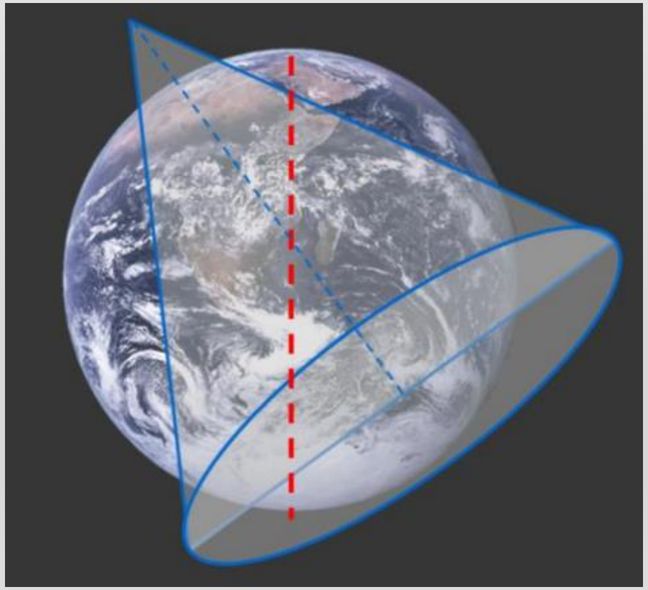
- Standard lines and points are important because those **corresponding places on the map will have no scale distortion**.
- The farther away from the standard point or line(s), the greater the distortion.
- Secants can help to minimise distortion over a large area by providing additional control.

PROJECTION ASPECT

- **Definition:** Position of the developable surface relative to the Earth
- A developable surface with the axis running from north to south pole creates a *normal aspect*



Normal aspect



Non-normal aspect

CENTRAL MERIDIAN AND PARALLEL; LATITUDE AND LONGITUDE OF ORIGIN

Central Meridian—Defines the origin of the x-coordinates

Longitude of Origin—Defines the origin of the x-coordinates; the central meridian and longitude of origin parameters are synonymous.

Central Parallel—Defines the origin of the y-coordinates

Latitude of Origin—Defines the origin of the y-coordinates; this parameter may not be located at the center of the projection. In particular, the conic projections use this parameter to set the origin of the y-coordinates below the area of interest.

SCALE FACTOR

- Scale factor is a unitless value applied to the center point or line of a map projection.

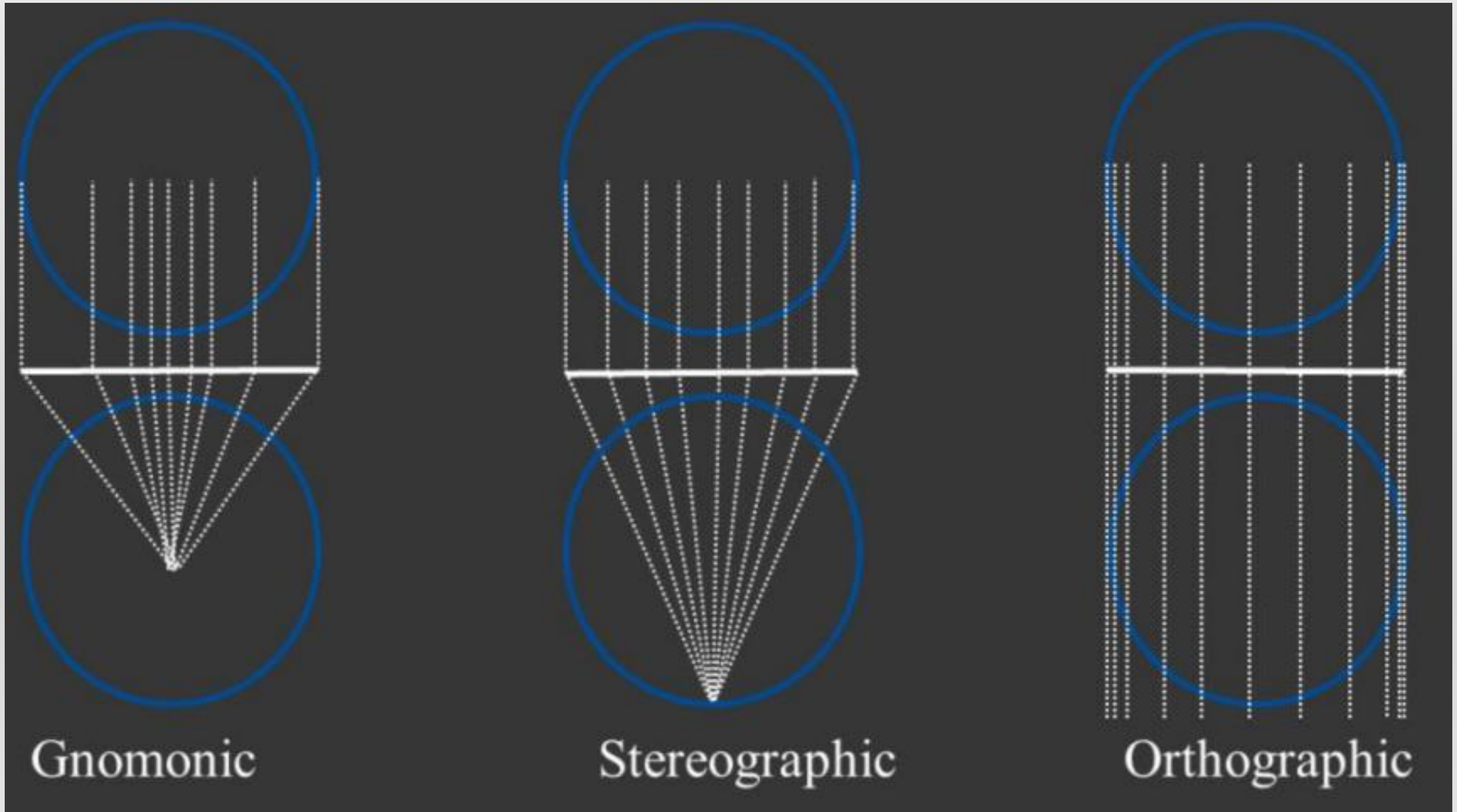
  The scale factor is usually slightly less than one. The UTM coordinate system, which uses the Transverse Mercator projection, has the scale along the central meridian of the projection is 0.9996. This creates two almost parallel lines approximately 180 kilometers, or about 1°, away where the scale is 1.0. The scale factor reduces the overall distortion of the projection in the area of interest.

FALSE NORTING AND FALSE EASTING

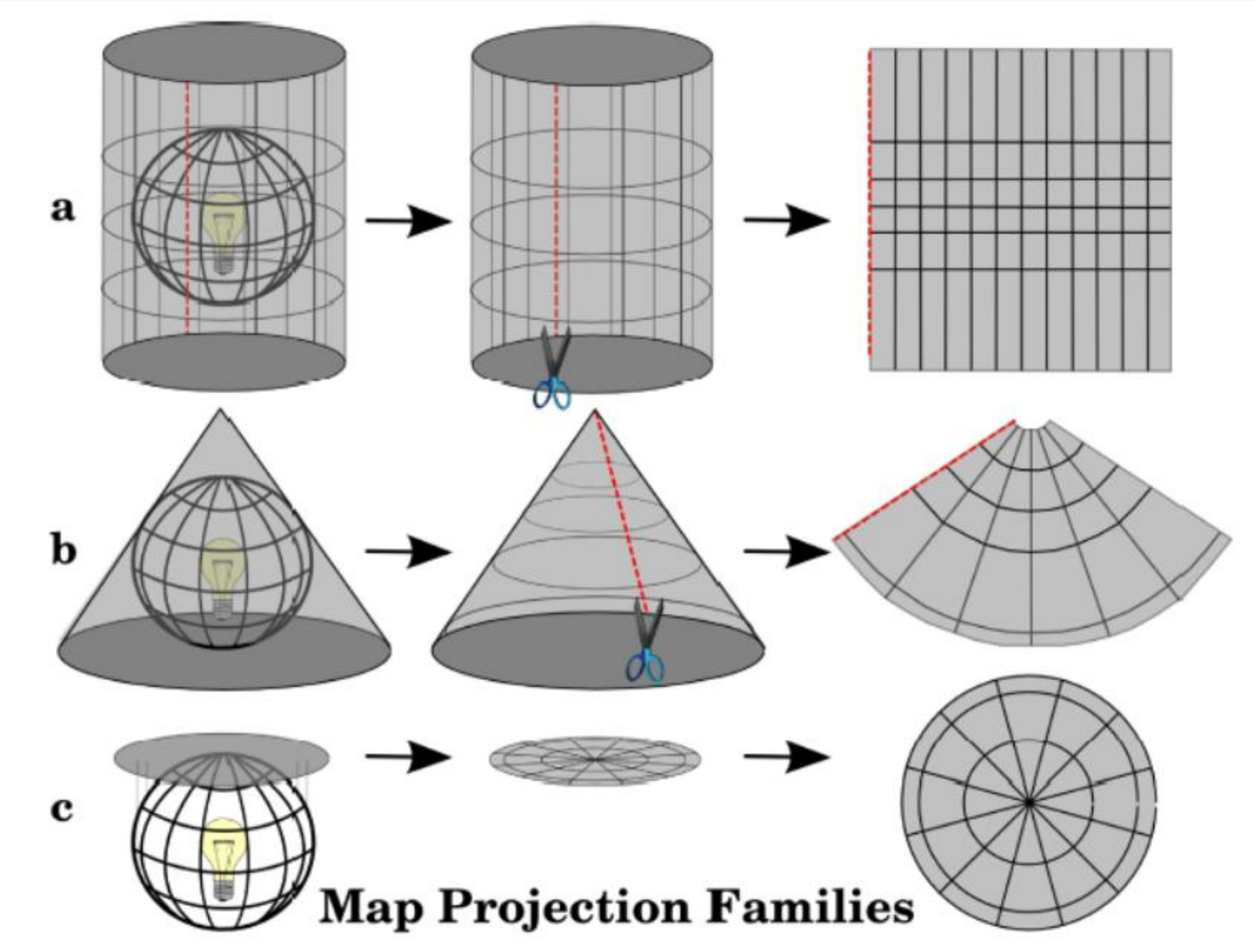
- False easting is a linear value applied to the origin of the x coordinates. False northing is a linear value applied to the origin of the y coordinates.
- False easting and northing values are usually applied to ensure that all x and y values are positive. You can also use the false easting and northing parameters to reduce the range of the x or y coordinate values. For example, if you know all y values are greater than 5,000,000 meters, you could apply a false northing of -5,000,000.

LIGHT SOURCE LOCATION

- **Definition:** The location of the hypothetical light source in reference to the globe being projected. There are three primary positions…



THREE MAIN MAP PROJECTION FAMILIES



cylindrical

conical

azimuthal

plus mathematical family

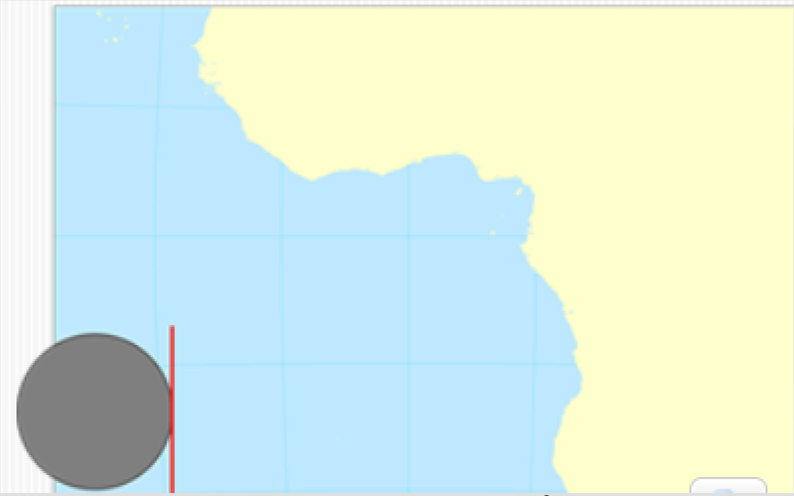
Source: „A Gentle Introduction to GIS” by Sutton, Dassau and Sutton

AZIMUTHAL FAMILY

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

polar

oblique

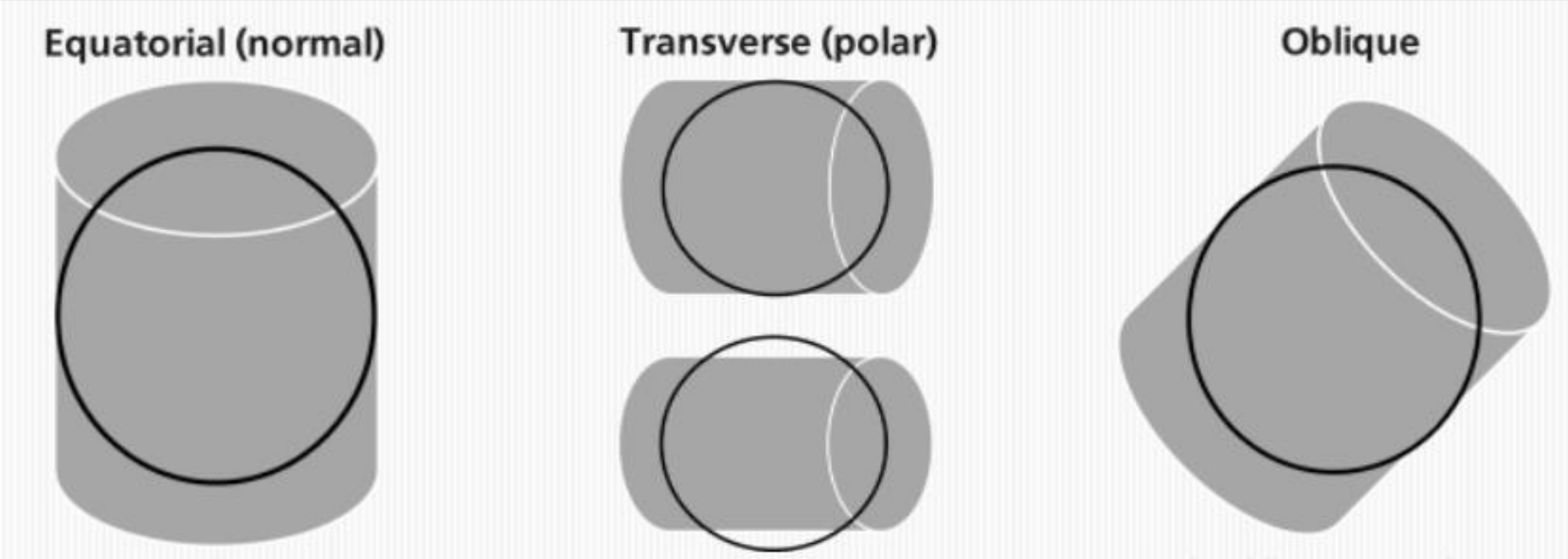


equatorial

CYLINDRICAL FAMILY

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

Three cylindrical aspects:



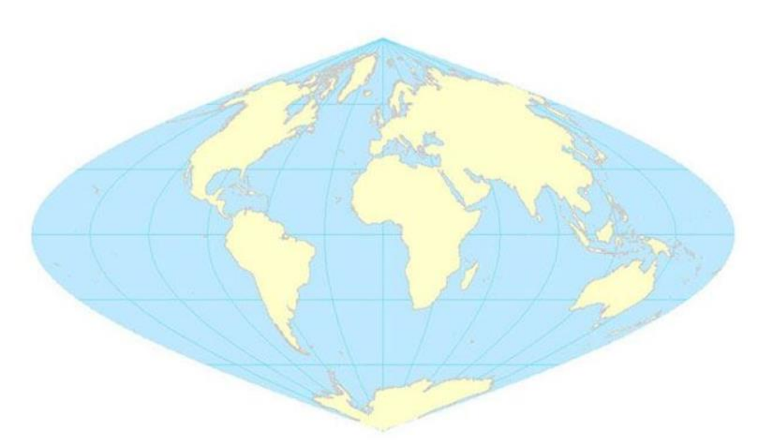
CONIC FAMILY

- In the conic family the developable surface is a cone on which the spheroid is projected. There is deformation and concentric bands parallel to the standard parallels of the map projection. The conic family is commonly used to display areas of Earth having a greater east-west extent.
- With the respect to aspects, the conic map projection family is typically presented in the normal aspect where the axis of the cone is in line with the axis of the spheroid.

MATHEMATICAL FAMILY

- To create a map projection of the mathematical family the spheroid is projected onto a mathematical surface that is not a cone, plane, or cylinder. Deformation can vary quite widely depending on the shape of the developable surface.
- Additionally, since the developable surfaces in this mathematical family can vary so greatly, there is no common map purpose that is used with the mathematical family of map projections. In some cases, developable surfaces in the mathematical family may resemble cylinders, cones, or planes that have been slightly deformed or warped for a specific need. In these cases, the developable surfaces may be referred to as pseudo-cylindrical, pseudo-conic, or pseudo-azimuthal.

sinusoidal



MAP PROJECTION PROPERTIES

- **<u>Definition:</u>** Alterations of area, shape, distance, and direction on map projections.
- All maps contain error because of the 3D→2D transformation process because rendering a spherical surface on a plane causes tearing, shearing, or compression of the surface. The four map projection properties are **area, shape, distance, and direction**. These four map projection properties describe four facets of a map projection that can either be held true or be distorted.

Major properties

- Area
- Shape

mutually exclusive

Minor properties

- Distance
- Direction

cannot be true everywhere on map

can co-exist with any of the other projection properties

MAP DISTORTIONS

- Distortions are unavoidable when making flat maps of a globe
- Distortion may take different forms in different parts of the map
- Few points where the distortions are zero
- Distortion is usually less near the points or lines of intersection where the map surface intersects the globe
- A map can show one or more - **but never all** – of the following at the same time:
  - ✓ True directions
  - ✓ True distances
  - ✓ True areas
  - ✓ True shapes

EQUAL AREA MAP PROJECTIONS

A.K.A.

equivalent map projection

Goal:

Preserve **area** relationships of all parts of the globe

Identifying marks:

Meridians and parallels are not at right angles to each other

Distance distortion is often present

Shape is often skewed

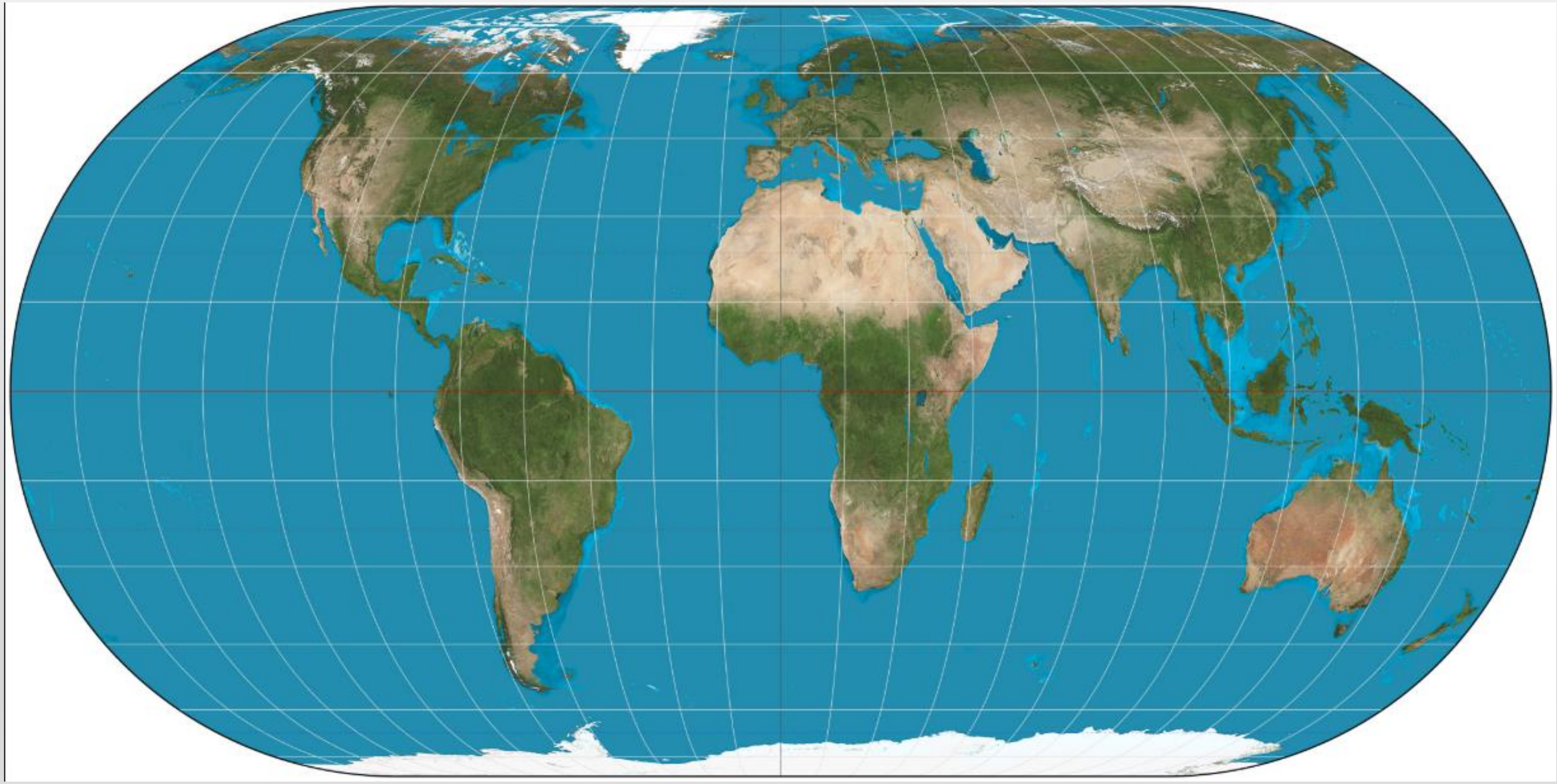
Useful for:

General quantitative thematic maps, especially on choropletic maps when the attribute is normalized by area

When it's desirable to retain area properties

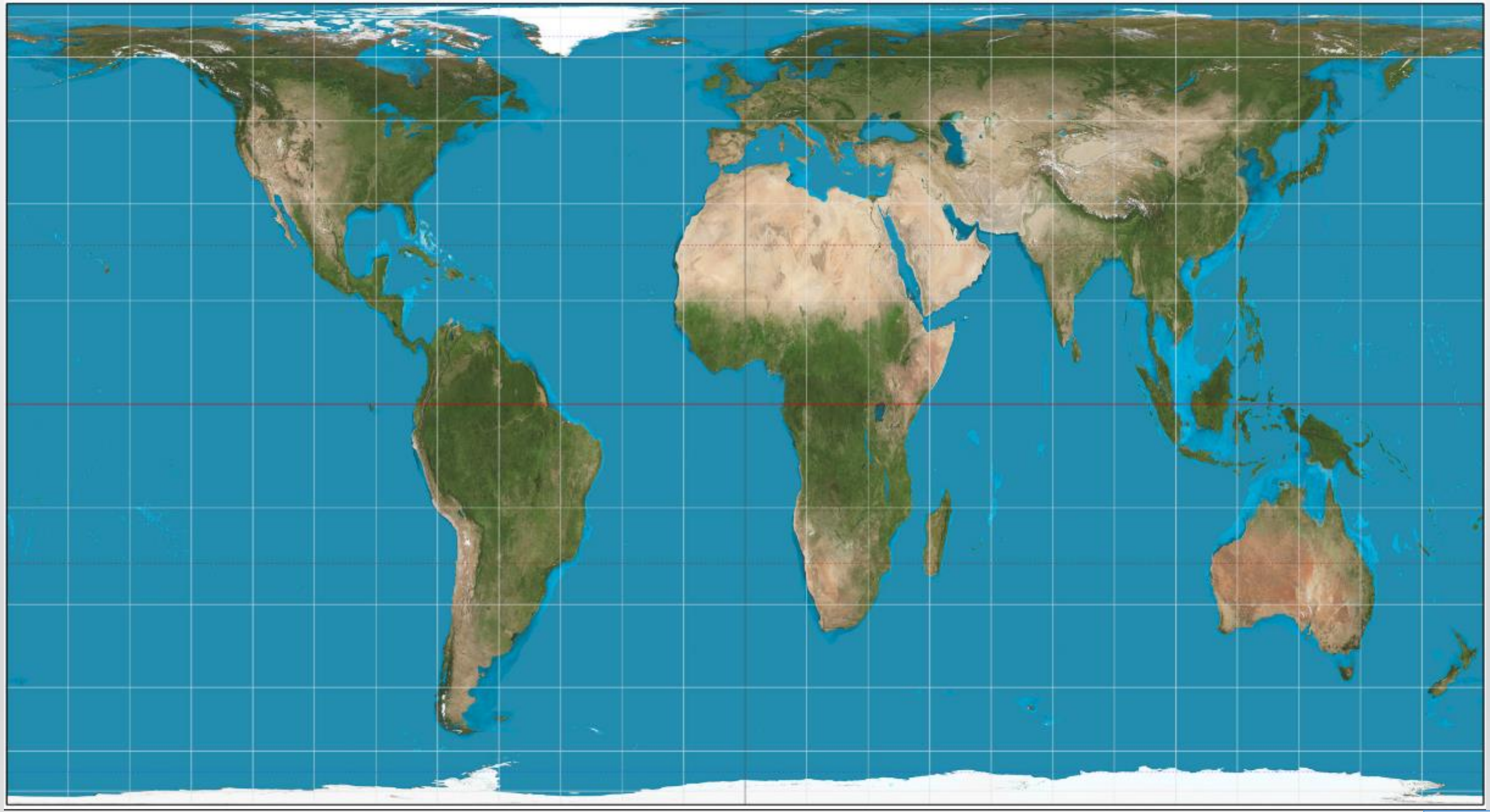
Area

ECKERT IV PROJECTION



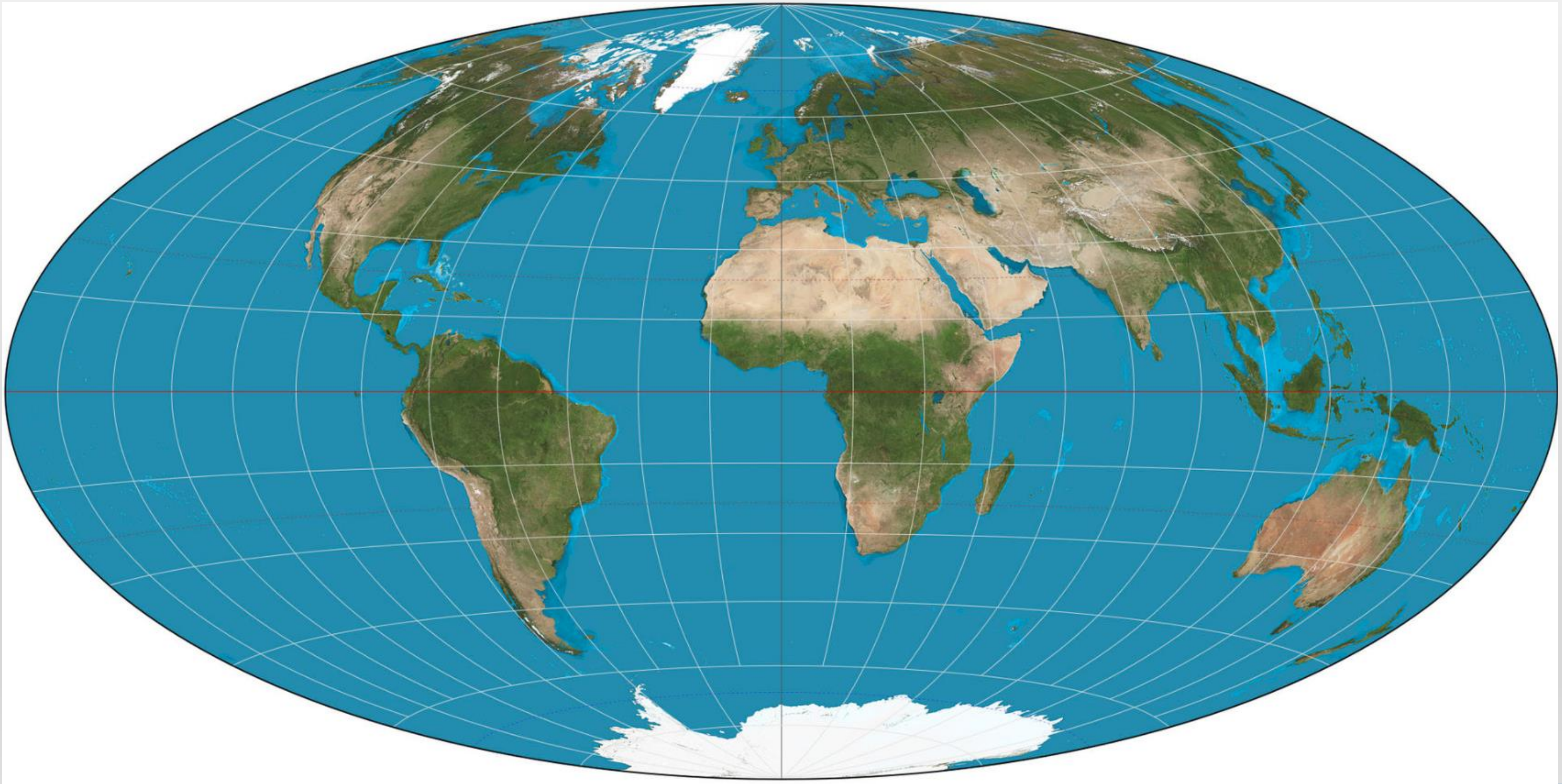
Area

CYLINDRICAL EQUAL AREA MAP PROJECTION



Area

HAMMER-AITOFF MAP PROJECTION



Area

CONFORMAL MAP PROJECTION

A.K.A

Orthomorphic map projection

Goal:

Preserve angles around points, and **shape** of small areas

Same scale in all directions

Identifying marks:

Meridians intersect parallels at right angles

Areas are distorted significantly at small scales

Shapes of large regions may be severely distorted.

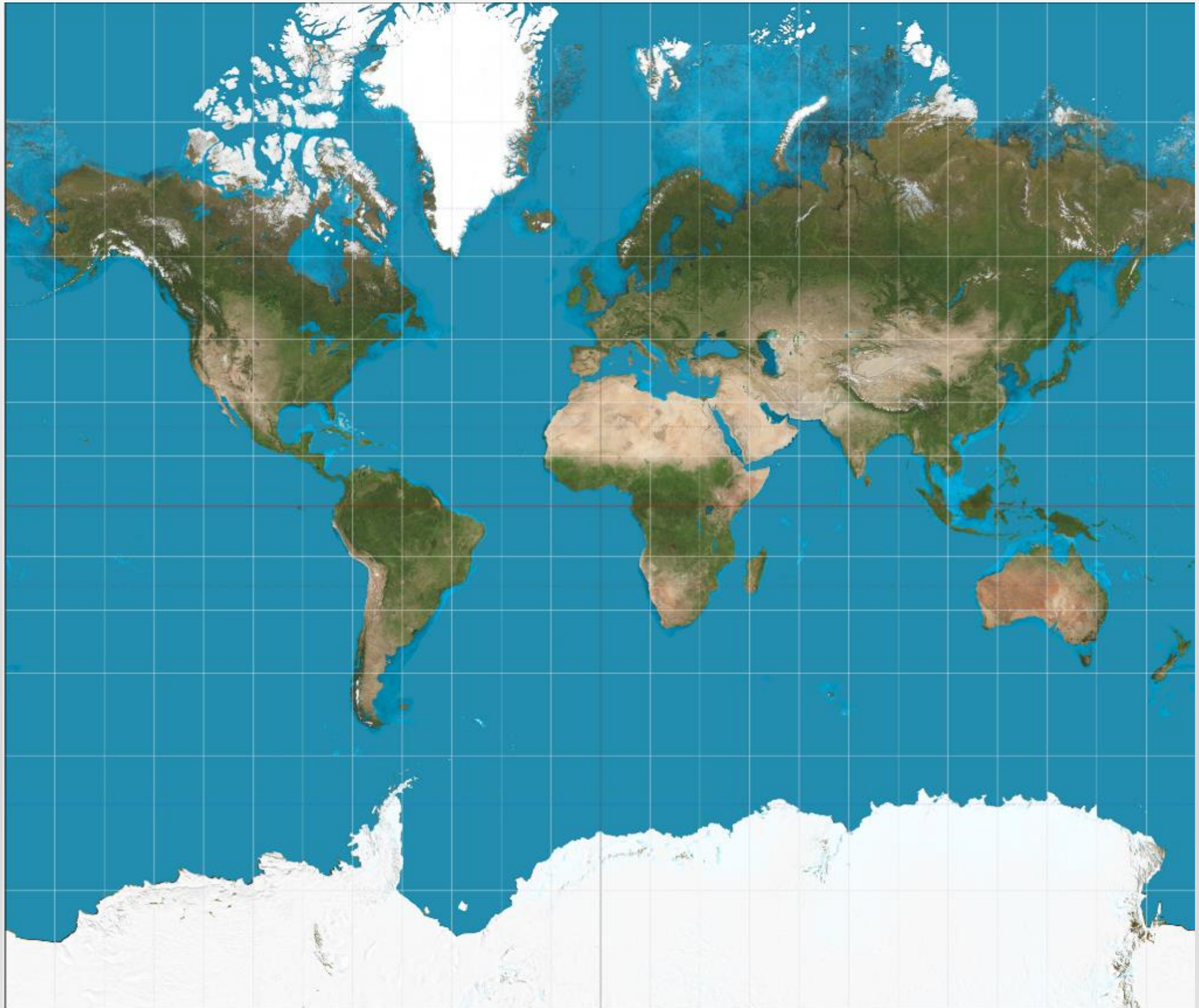
Useful for:

Large-scale mapping

Phenomena with circular radial patterns (e.g. radio broadcasts)

Shape

MERCATOR



Shape

Map projection comparison

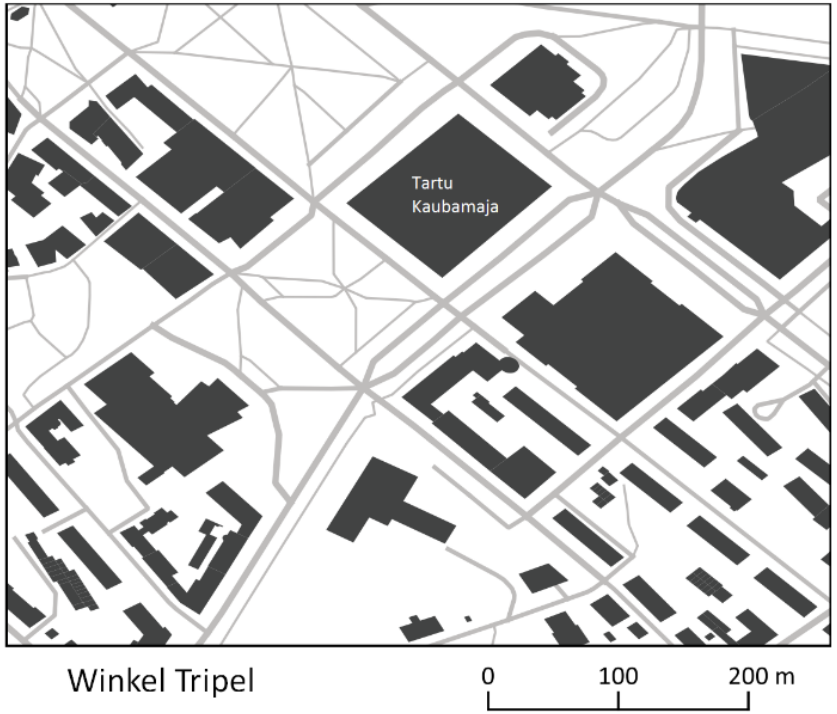
Most accurate

L-EST1997

Distorts area

Web Mercator

Distorts shape and area (minimal error projecion)



Winkel Tripel

EQUIDISTANT MAP PROJECTION

Goal:

Preserve great circle distances

Distance can be held true from one point to all other points, or from a few select points, to others, but **not from all points to all other points**.

Scale is uniform along the lines of true distance

Identifying marks:

Neither conformal nor equal area,

and look less distorted.

Useful for:

General purpose maps

Atlas maps

Distance

EQUIDISTANT CYLINDRICAL MAP PROJECTION

Distance

AZIMUTHAL MAP PROJECTION

A.K.A.

True direction

Goal:

Preserve direction from one point to all other points in the map

Direction is not true between non-central points.

Direction is only true when measured to or from the specific points chosen.

Useful for:

Preserving direction from one point

Often used for navigation

Direction

AZIMUTHAL EQUIDISTANT MAP PROJECTION

Direction

COMBINATION OF PROPERITES ON A SINGLE PROJECTION

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

Yes denotes that they can be combined

No denotes that they cannot be combined

MINIMAL ERROR MAP PROJECTION

A.K.A.

Compromise map projection

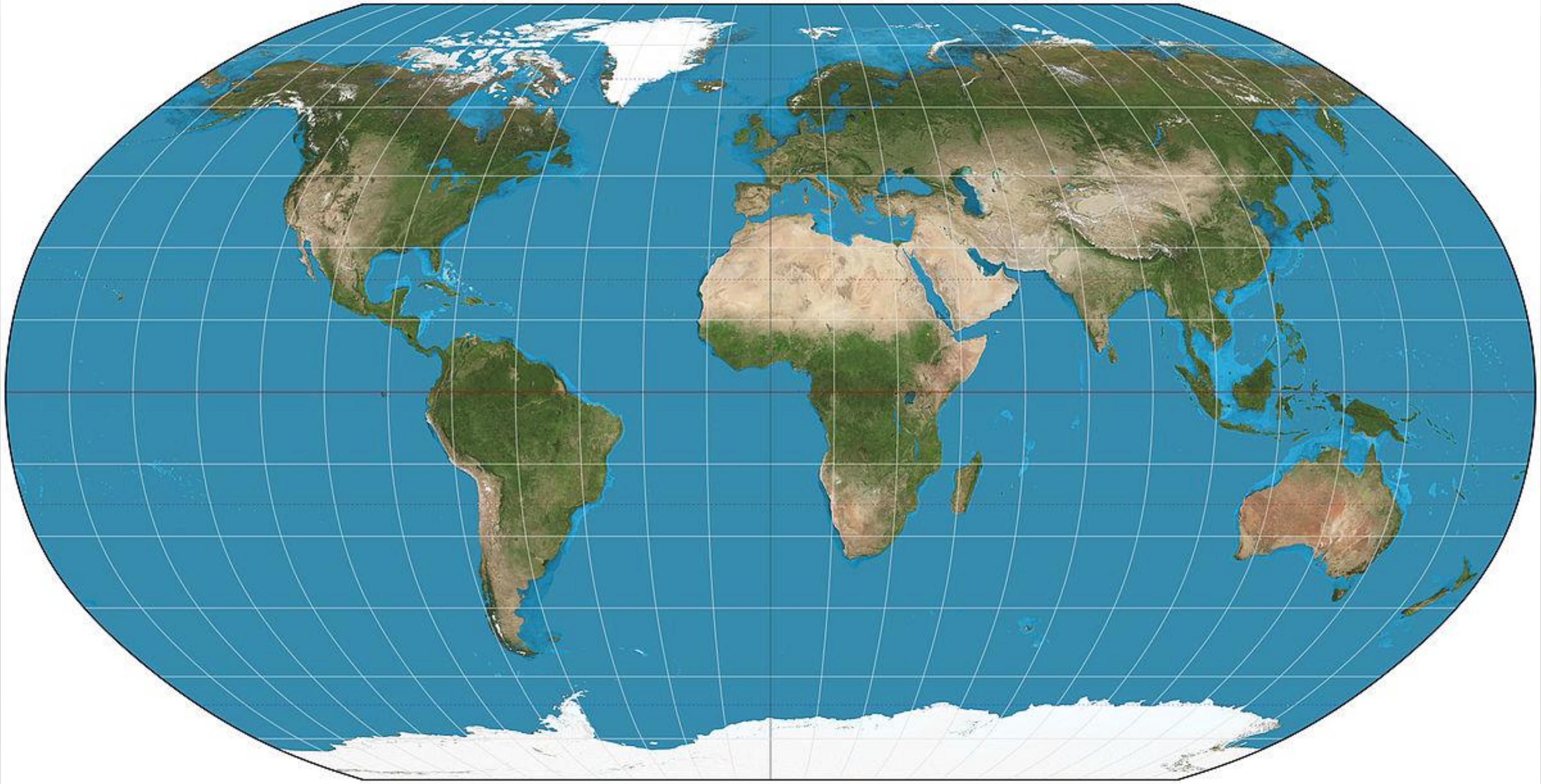
Goal:

Simultaneously minimize all four map projection properties

Useful for:

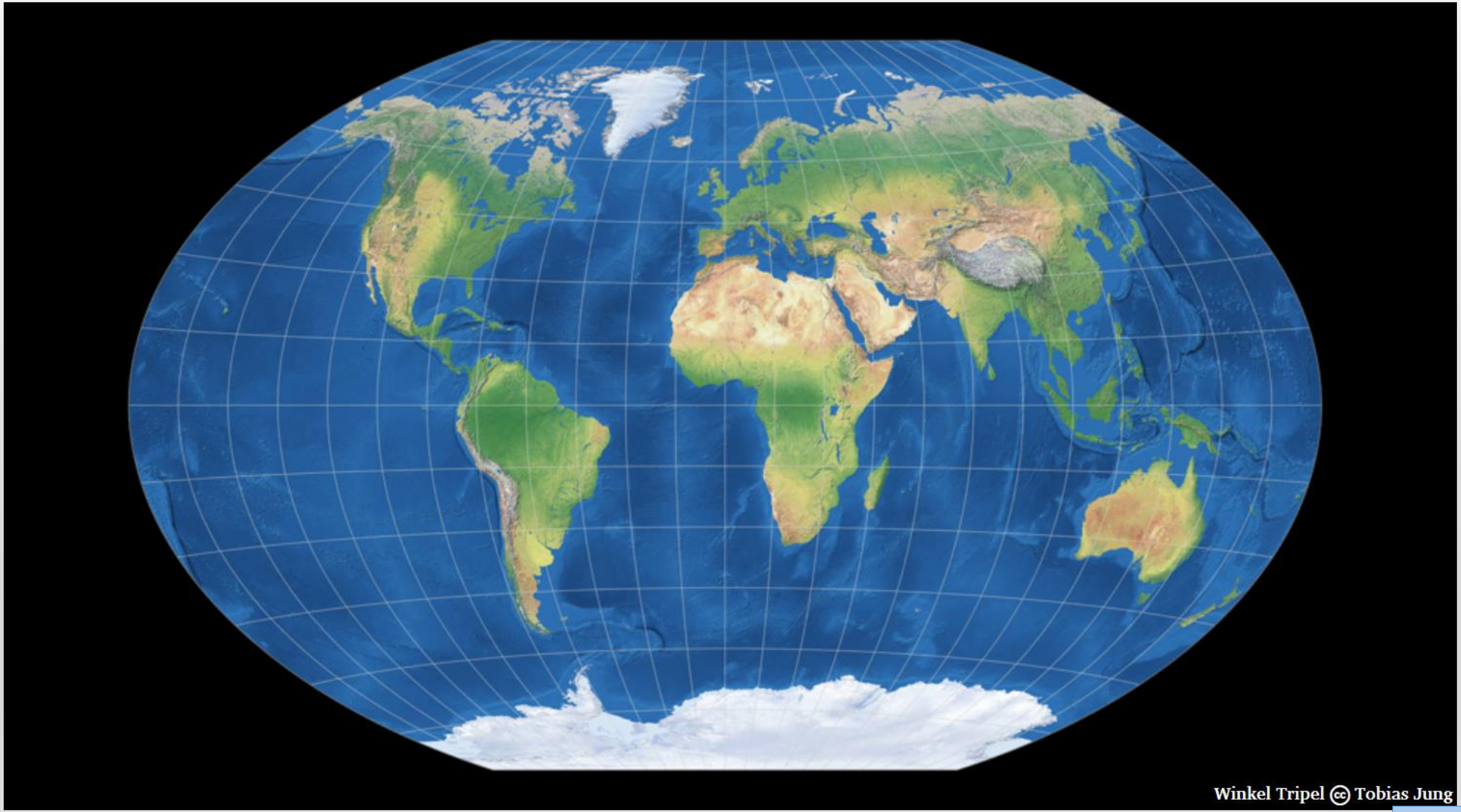
General geographic cartography

ROBINSON PROJECTION



Minimal Error

WINKEL TRIPEL



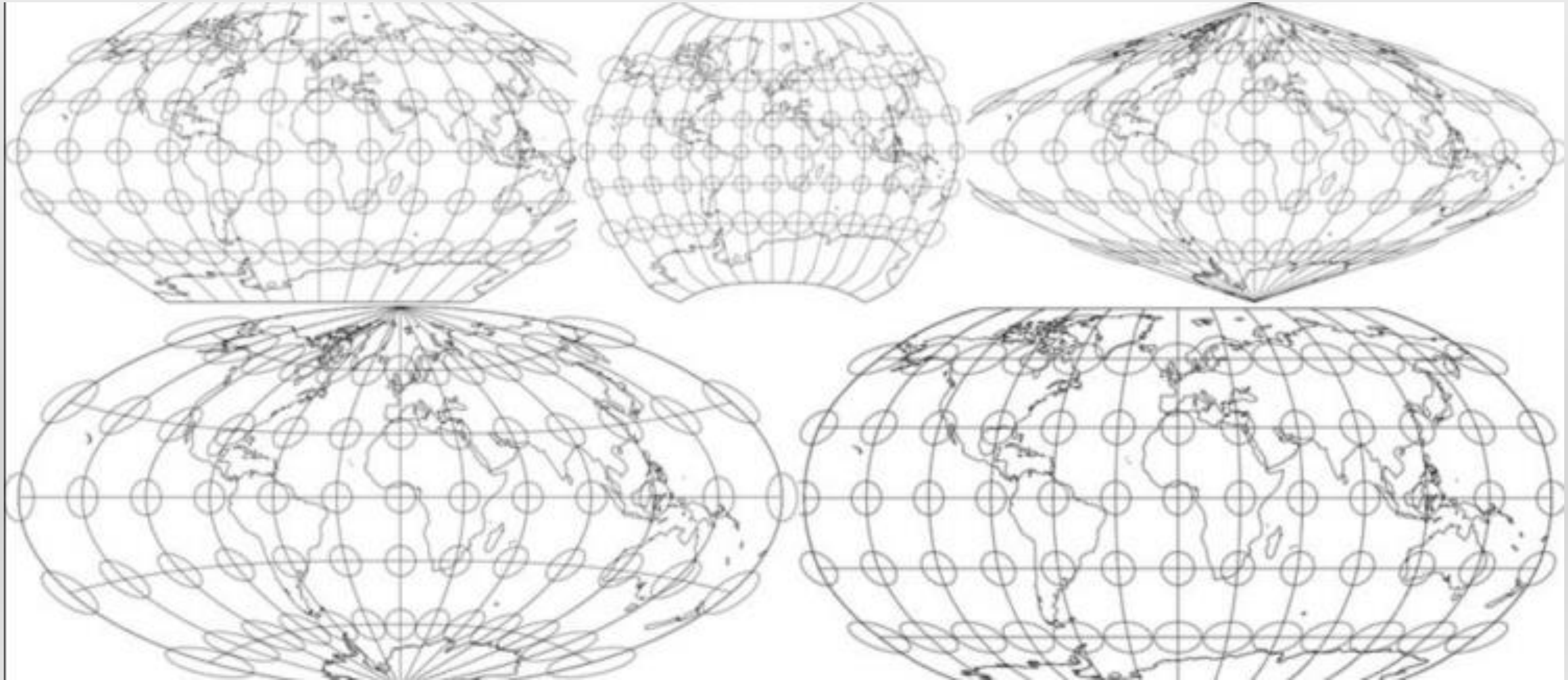
Minimal Error

DETERMINING DEFORMATION AND ITS DISTRIBUTION OVER THE PROJECTION

- All flat maps distort shape, area, direction, or length
- **Tissot's Indicatrix** helps to quantify distortion and projection properties
- Composed of small circles centered at points on the Earth
- Consider the shape of the circles after projecting the map to determine the deformation and distribution of error throughout the map

TISSOT'S INDICATRIX

Interpretation: see what happens to the circles when you project



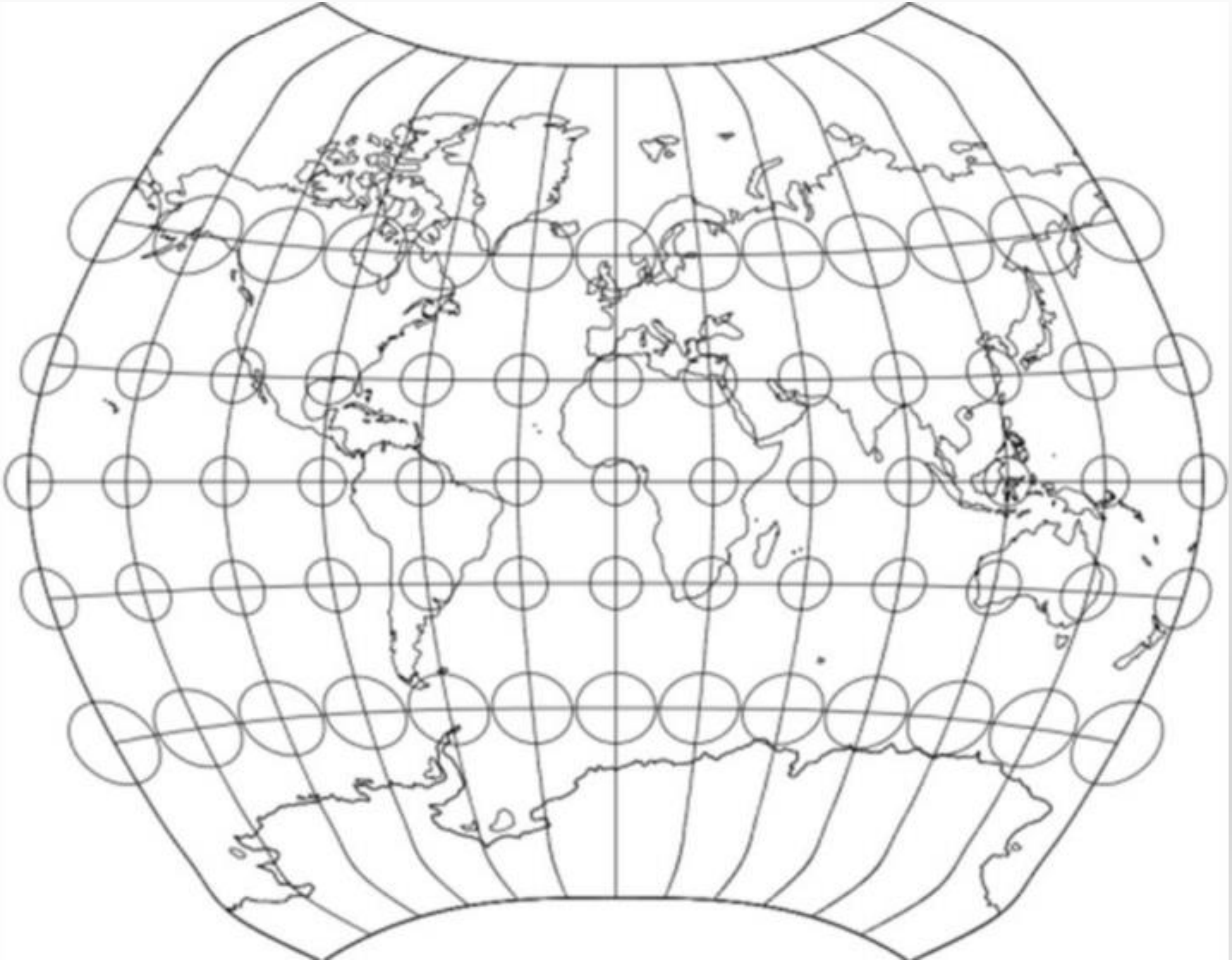
INTERPRETING TISSOT'S INDICATRIX

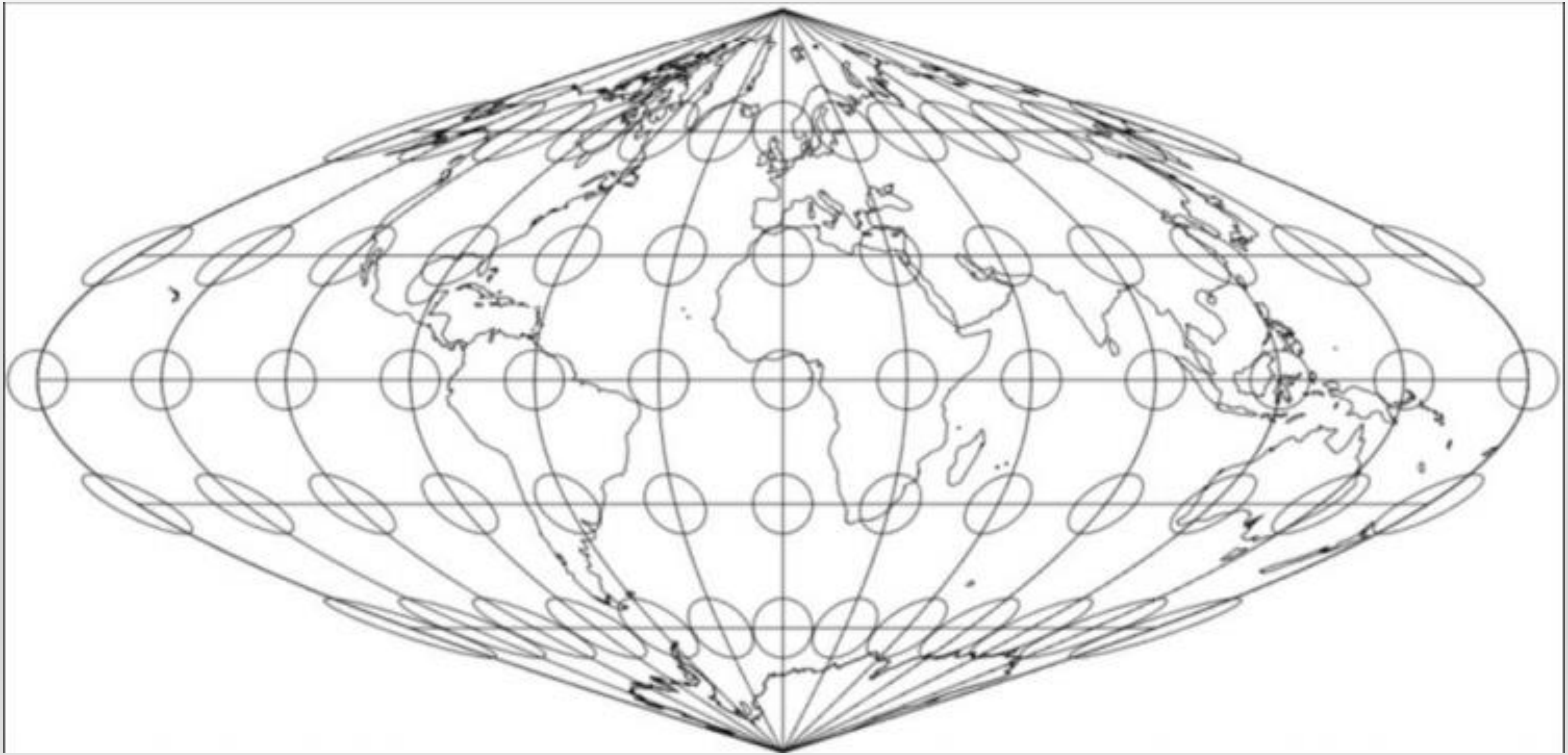
Equal Area:

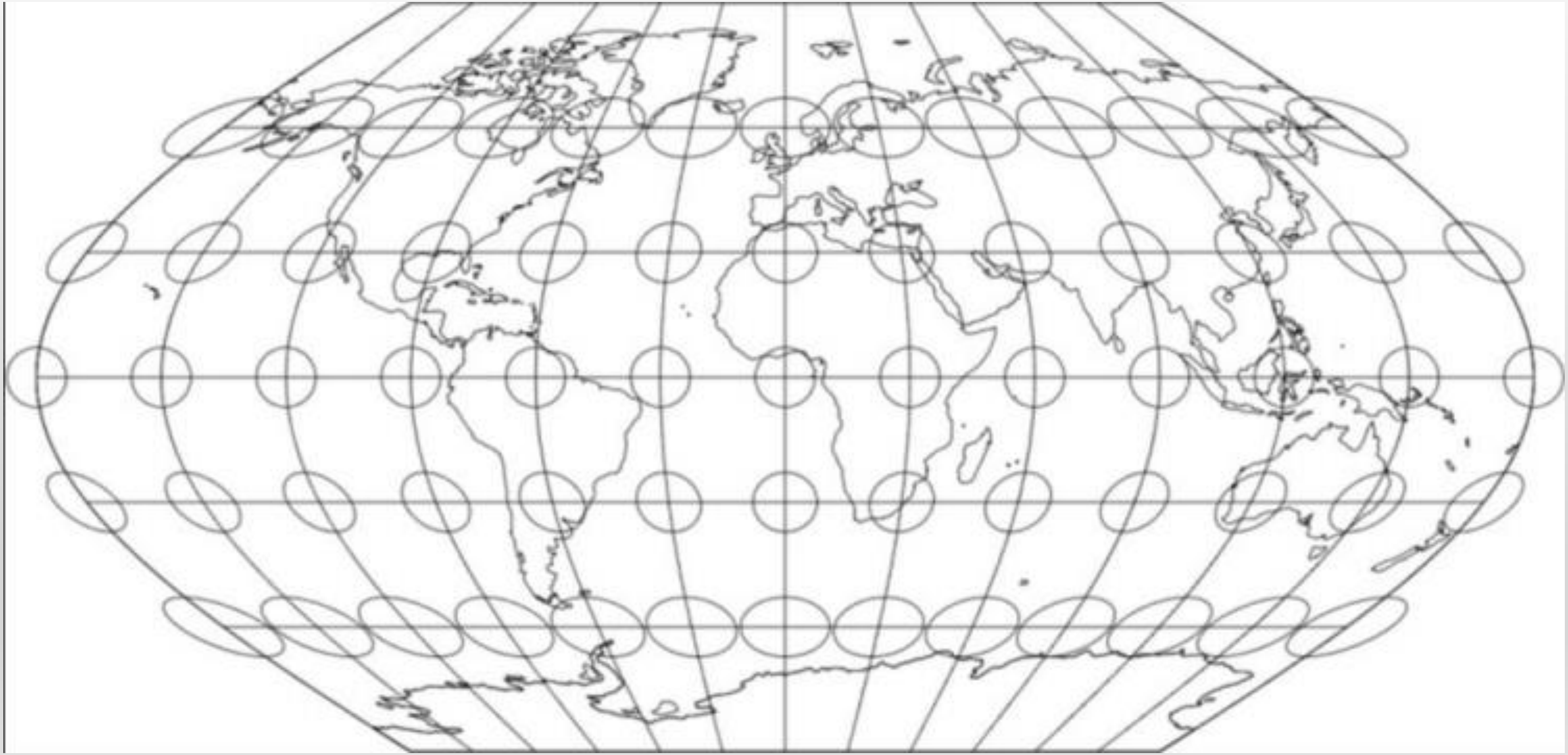
Circle transformed into elllipse, but area remains the same.

Conformal:

Circle transformed as circle, but size varies over the map.

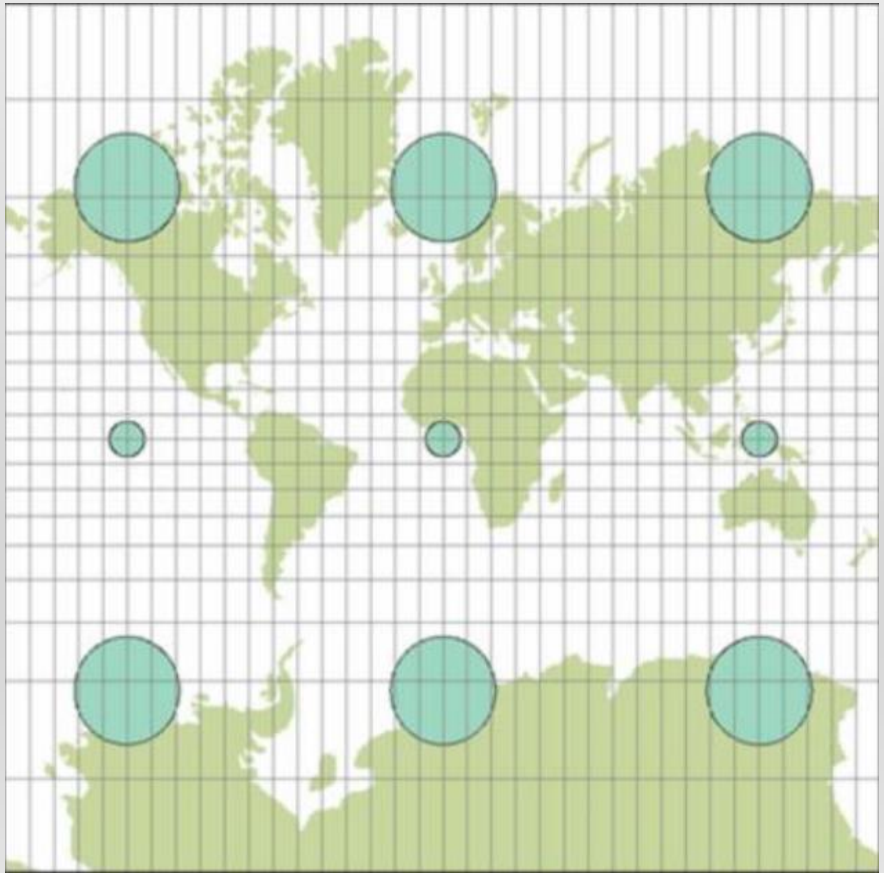






CONFORMAL PROJECTION PROPERTY

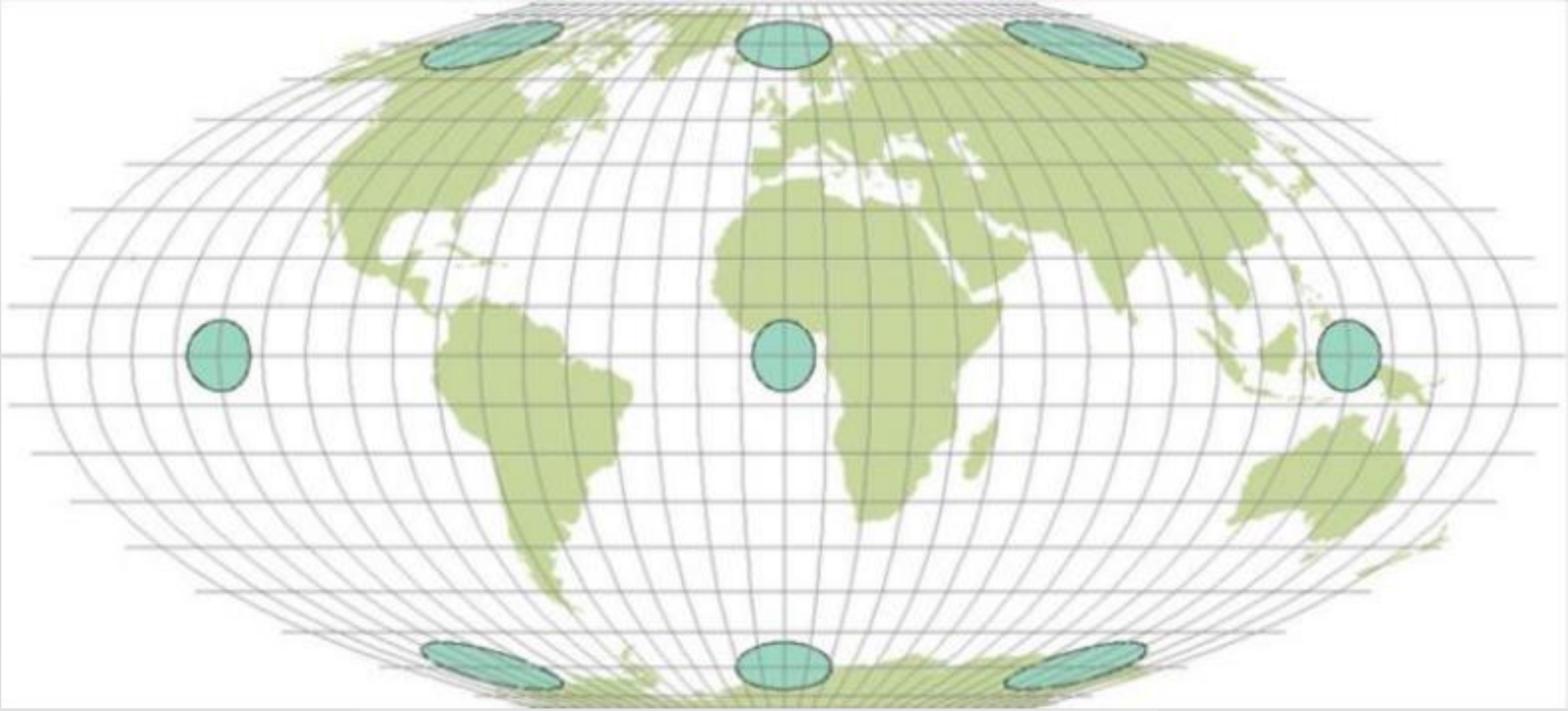
Conformal – ellipse would remain circular, although most likely larger or smaller than original circle.



Mercator

EQUAL AREA PROJECTION PROPERTY

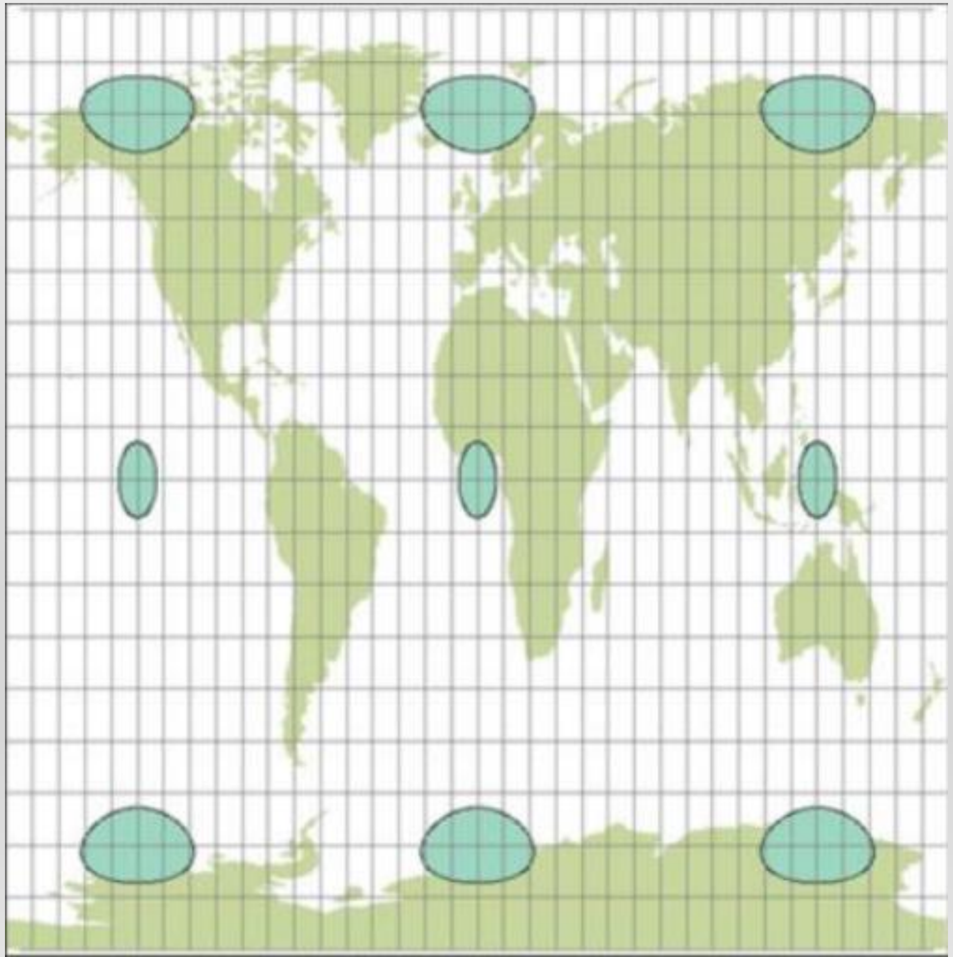
Equal area – circle would not have same shape but would have the same area as original.



Flat-Polar Quartic Projection

OTHER PROJECTION PROPERTIES

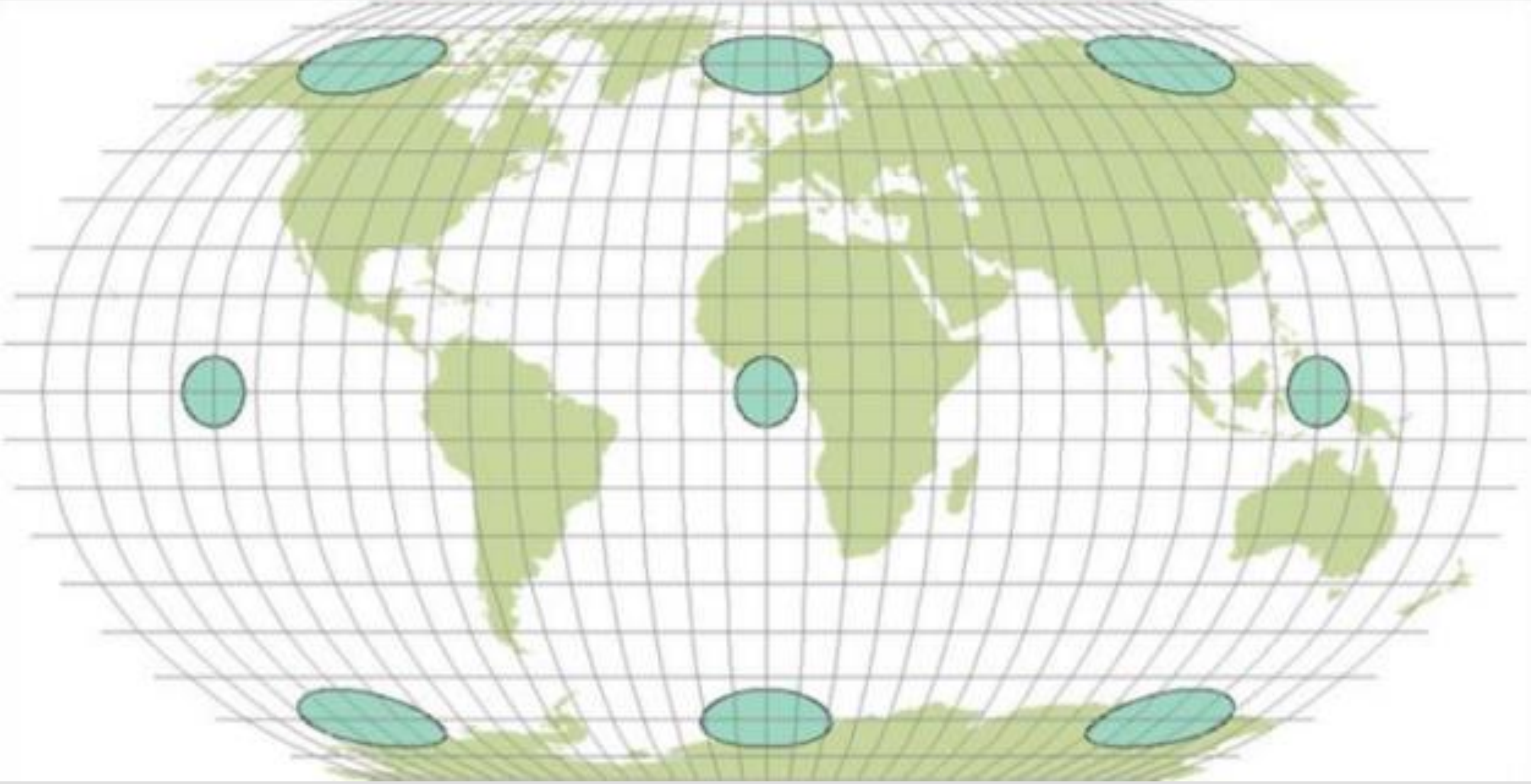
- Equidistant – distances are true between two points



Equidistant Cylindrical Projection

OTHER PROJECTION PROPERTIES

Minimal error projections that distort a little bit of everything



Robinson Projection

WHEN CHOOSING A PROJECTION

When choosing a projection in which to store your database, consider the database's primary use.

- Databases created under contract or to be used by a government organisation are often in a projection determined by the governing body, such as state plane in the United States or Great Britain National Grid in the United Kingdom.
- Use equal area projections for thematic or distribution maps.
- Presentation maps are usually conformal projections, although compromise and equal area projections can also be used.
- Navigational maps are usually Mercator; true direction, and/or equidistant.

Source: ESRI

Other considerations for map projection choice

- The extent of the area to be mapped. Is it a database of the world, a continent, or a state?
- Location of the area to be mapped. Is it a polar, mid-latitude, or equatorial region?
- Predominant extent of the area to be mapped. Is the area roughly circular or longer in the east–west, north–south, or some oblique direction?

CONCLUSION

- When you import spatial data into GIS program, you must know the projection, if any, 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.
- It is important that if you plan on doing **any spatial analysis with your data, that you first project the data in to the same coordinate system to get maximum accuracy**.

LAB SESSION

- You will explore the effects of various map projections on the characteristics of a map using QGIS. The lab session will examine projections useful for mapping on the global scale as well as on the national level.

INDEPENDENT TASK

Make presentation and upload pdf file on following:

- Find out what **horizontal and vertical datum is used in your country** and if and how it has changed through time.
- What is the national **projected coordinate system** for your country – give the specifics, peculiarities.
- Add maps from your country in different coordinate systems (WGS84, national PCS and UTM) from the Lab session task. The maps should include graticule.

ADDITIONAL READING

- See in Moodle, Chapter 3 from Bolstad (2008).
- Flex Projector is a freeware, cross-platform application for creating custom world map projections.
- Compare Map Projections is an excellent webpage to compare different projections or just check how various projections look like.

REFERENCES

- The lecture is largely based on FOSS4G Academy Curriculum materials licensed under the Creative Commons Attribution 3.0 Unported License
- USGS Projection Map USGS Projection Map