

ISA

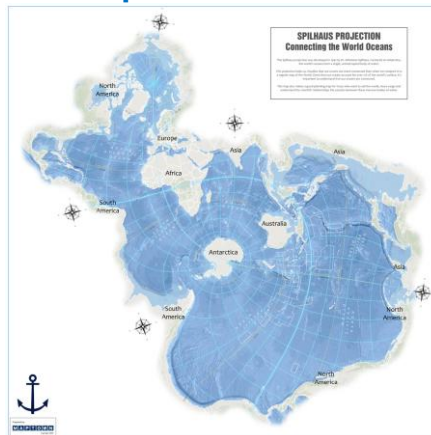
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Lesson 10 - Coordinate Reference Systems

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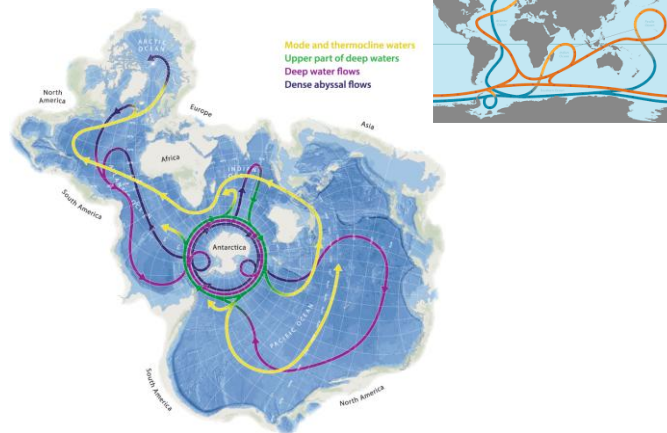
UNIVERSIDADE
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AGRONOMIA

What does this represents?



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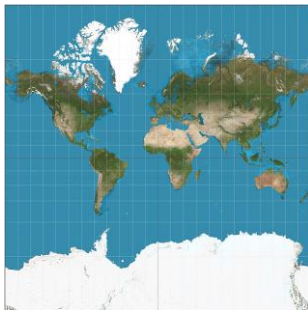
Is it useful?



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What is the best map?

Mercator projection (1569)



Robinson projection (1963)



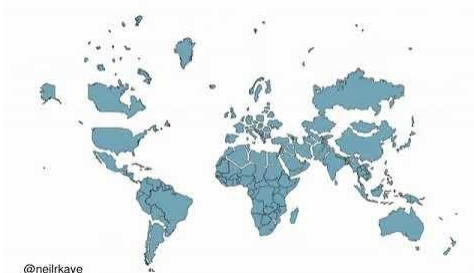
Equal-area map projection (2018)



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What is the best map?

World Mercator projection with country going to true size

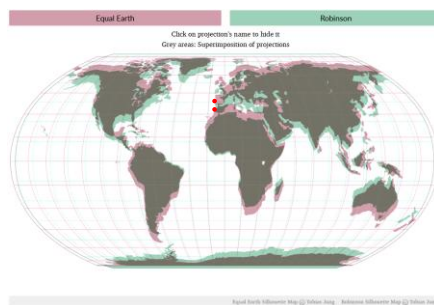


<https://www.youtube.com/watch?v=G5xCOH15ZZs>

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Why CRS Matter in GIS

- Accurate representation of Earth's surface in maps and datasets.
- Without proper CRS, GIS data may not align correctly
- CRS is essential for integrating spatial data from different sources.
- Errors in CRS selection or transformation can distort maps and analysis results.



CRS ensures you can accurately analyze and visualize geographic data

Without the correct CRS, your GIS data may not align with reality

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1. Geodesy definition

γῆ + δαίω

What is it?

- Ancient Greek: "geo" meaning Earth & "daisia" meaning to share or distribute
- The science of measuring and dividing the Earth's surface
- Started by Gauss (1843)

International Association of Geodesy (IAG):

- "science of determining the size & figure of the earth, and its external gravity field"

National Oceanic and Atmospheric Administration (NOAA):

- "science of accurately measuring & understanding three fundamental properties of the Earth: its geometric shape, its orientation in space, & its gravity field— as well as the changes of these properties with time"

scientific discipline focused on precisely measuring and understanding Earth's geometric shape, gravitational field, and rotational dynamics, while also extending these principles to other celestial bodies

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1. Geodesy objectives

- Determining the Earth's shape and size
- Model Earth's gravity field to define elevation and sea-level variations
- Understanding Earth's rotation and orientation
- Establish reference systems for consistent global positioning
- Monitor geodynamic phenomena:
 - Earth's deformation (earthquakes, volcanic activity)
 - Tectonic movements
 - Ice sheet mass balance
 - Post-glacial rebound
- Facilitating global navigation and satellite positioning
- Contributing to Earth sciences and climate research
- Supporting surveying, mapping, and infrastructure development

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1. Geodesy core components

- Earth Models
 - Geoid
 - Ellipsoid
 - Datum
- Reference Systems
 - Terrestrial Reference System (TRS)
 - Coordinate Reference System (CRS)
- Coordinate Systems
 - Geographic Coordinate System (GCS)
 - Projected Coordinate System (PCS)

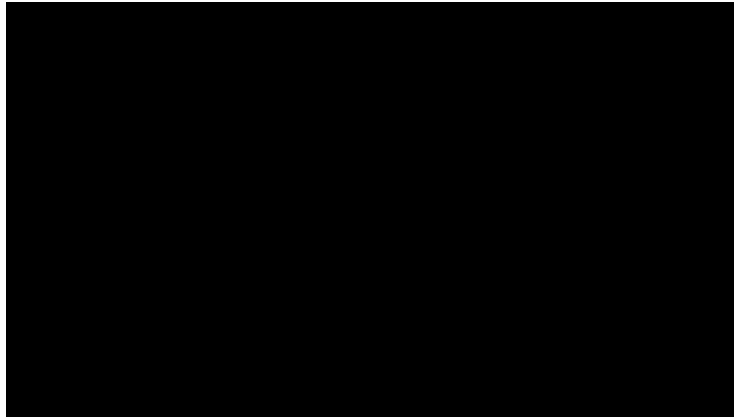
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Topics

1. Geodesy
2. Earth's Shape and Models
 - Ellipsoid
 - Geoid
 - Datum

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2. Earth's Shape and Models

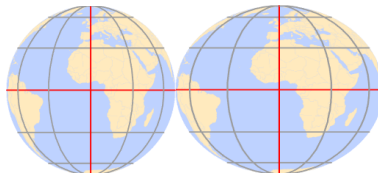


<https://www.youtube.com/watch?v=srYyJBa9Zwk&t=11s>

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2. Earth's Shape and Models

- Assuming earth is a perfect sphere simplifies mathematical calculations
 - works well for small-scale maps (showing large areas of earth)
- An ellipsoid representation of earth provides more accuracy when working at large-scale maps
 - this shape is a consequence of the centripetal force along the equator due to Earth's rotation
- Differences in distance measurements along surfaces of an ellipsoid vs. a sphere are small but measurable (up to 21km)



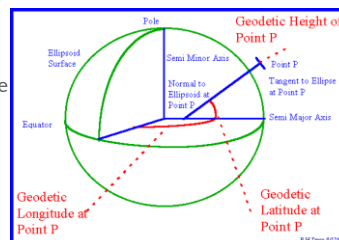
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2. Earth's Shape and Models - Ellipsoid

- Ellipsoid is defined by two radii
 - semi-major axis (the equatorial radius)
 - semi-minor axis (the polar radius)
- Satellite & computational capabilities allow precise estimates of these radii
- Has a totally smooth surface across the world
- Not reflecting local variations in elevation
- Does not reflect the undulating nature of the earth's surface



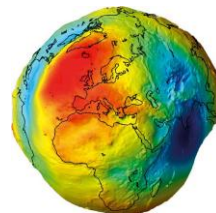
Geoid



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2. Earth's Shape and Models - Geoid

- Aims to represent Earth's "true" shape
- Not a perfect sphere or ellipsoid, its **irregular due to variations in the Earth's gravity field** (approx. the same as **global mean sea level**) caused by the uneven distribution of mass
 - considers gravitational effects of mountains, ocean trenches & density variations in Earth's interior
- Hypothetical surface **representing the shape Earth's oceans would take under the influence of gravity alone**, assuming the absence of other forces such as tides & currents
 - equipotential surface, i.e., at any given point on the geoid, the gravitational potential is the same

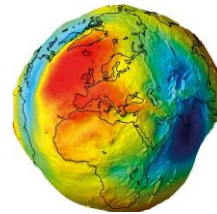


Exaggerated representation

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2. Earth's Shape and Models - Geoid

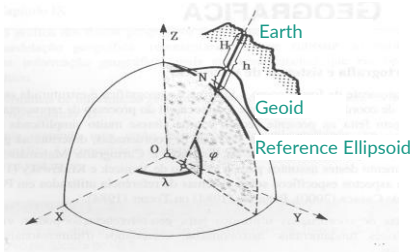
- Geoid models are **mathematical models & representations** based on precise measurements of the Earth's gravity field
 - continually refined & updated with new data to improve geoid representation accuracy
- Serves as a reference surface for measuring elevations on the Earth
 - presently, the standard model (Earth's Gravitational Model – EGM96) uses 360 coefficients



Exaggerated representation

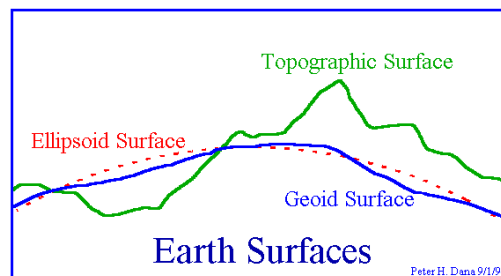
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2. Earth's Shape and Models



The solution is to align the geoid with the ellipsoid and map earth's surface features onto the ellipsoid

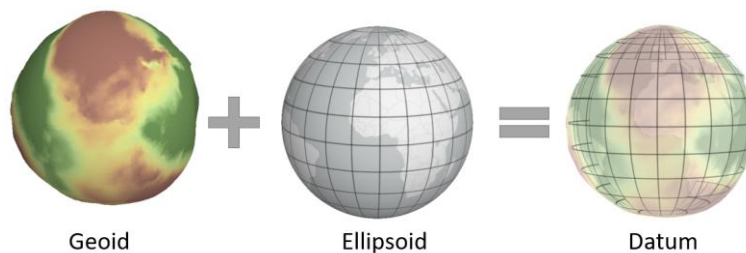
So, how do we reconcile these 2 models?



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2. Earth's Shape and Models - Datum

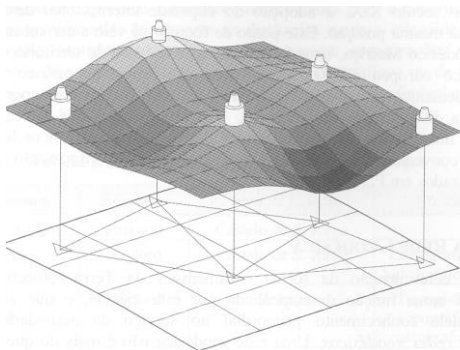
The solution is to align the geoid with the ellipsoid and map earth's surface features onto the ellipsoid, defining a Datum



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2. Earth's Shape and Models - Datum

Establish a network of Geodesic points (and their projections on a reference plane)



- geodesic point: location where the coordinates in relation to the ellipsoid are determined with maximum accuracy

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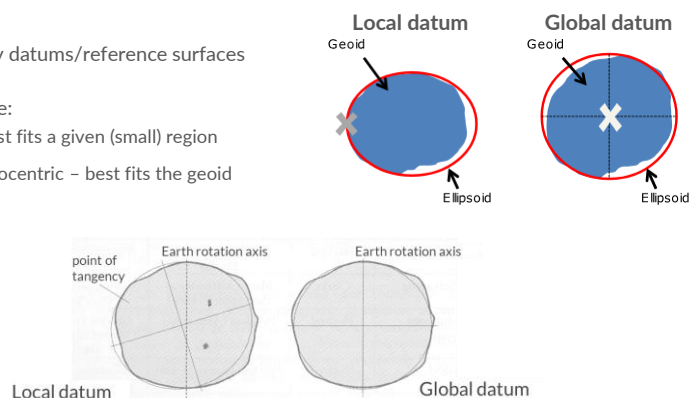
2. Earth's Shape and Models - Datum

- model that defines the shape and size of the Earth's surface, as well as the location of a reference point (the origin) and the orientation of the axes
- provides the framework for measuring and comparing positions on the Earth's surface
- an abstract coordinate system with a reference surface that serves to provide known locations to begin surveys & create maps
- Key Components:
 - **Reference Ellipsoid**: describes the shape of the Earth (e.g., WGS 84).
 - **Geodetic Centre**: specifies the Earth's centre point.
 - **Prime Meridian**: defines the longitudinal reference line (e.g., Greenwich Meridian).

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2. Earth's Shape and Models - Datum

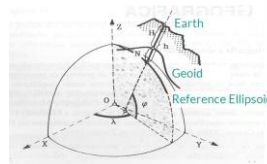
- There are many datums/reference surfaces
- A Datum can be:
 - Local – best fits a given (small) region
 - Global/Geocentric – best fits the geoid



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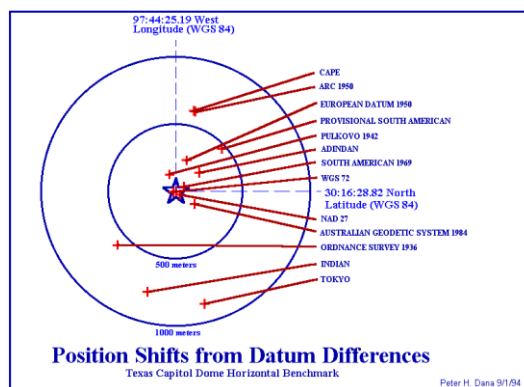
2. Earth's Shape and Models - Datum

- A Datum can be:
 - Horizontal – prioritizing accurate planar positioning (latitude/longitude)
 - used for describing the location of points on the earth's surface, using an ellipsoidal or other coordinate systems
 - Vertical – focusing on elevation accuracy, used to measure elevations or depths
 - Orthometric height or mean sea level (MSL) elevation (H) refers to the distance to the geoid (e.g. elevation used in Topography);
 - Ellipsoidal (geodetic) height (h) is the distance to the reference ellipsoid (e.g. elevation provided by the Global Positioning System – GPS).
 - $N = h - H$ is called the geoid height or geoid undulation.



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2. Earth's Shape and Models - Datum



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Topics

1. Geodesy
2. Earth's Shape and Models
3. Reference Systems (TRS)
 - Terrestrial Reference System (TRS)
 - Coordinate Reference System (CRS)

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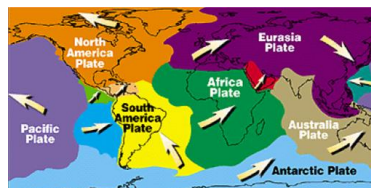
3. Reference Systems

- We can mention 2 levels reference systems:
 - Terrestrial Reference System (TRS)
 - Coordinate Reference Systems (CRS)

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3. Reference Systems - TRS

- Theoretical framework co-rotating with the Earth in its daily motion, providing a stable 3D spatial reference for measuring positions on Earth's surface
 - In such a system, locations on Earth's surface may have coordinates which only suffer quite small variations with time due to geophysical effects – tectonic or tidal deformations.



- Key Components:
 - Origin: Earth's center of mass (geocenter).
 - Orientation:
 - Z-axis: Aligned with Earth's mean rotational axis
 - X-axis: Intersection of equatorial plane & Greenwich meridian
 - Scale: Consistent metric definition (e.g., SI meters)
 - Time Evolution: Accounts for tectonic drift (~2.5 cm/yr) and tidal deformation

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3. Reference Systems - TRS

- The International Earth Rotation and Reference Systems (IERS) defines and maintains the TRS and its Terrestrial Reference Frames (TRF) realizations
 - 7 parameters are needed to fix a TRF at a given epoch.
- Implementation examples:
 - Global:
 - ITRF: International Terrestrial Reference Frame (e.g., ITRF2020, ITRF2020-u2023).
 - WGS84: GPS standard (aligned with ITRF).
 - Regional:
 - ETRS89: Fixed to Eurasian tectonic plate.

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3. Reference Systems - TRS vs. Datum

TRS are the conceptual framework that defines rules for the implementation, i.e., building datums

Aspect	TRS	Datum
Role	Theoretical framework (rules).	Practical realization (implementation).
Realization	Not directly usable.	Defines coordinates for mapping/GPS.
Examples	ITRS, ETRS89 (European system).	ITRF2020, WGS84, NAD83.

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3. Reference Systems - CRS

- Coordinate Reference Systems (CRS) operationalize TRS into usable coordinates to map Earth's surface
- CRS are a practical system for assigning coordinates to geographic data, combining:
 - **Datum:** Links coordinates to Earth's surface (horizontal/vertical).
 - **Coordinate System:** Rules for expressing positions (e.g., latitude/longitude, UTM).
- **Key Components:**
 - Horizontal Datum (1 or the other):
 - Geodetic: Tied to an ellipsoid
 - Local: Optimized for regions
 - Vertical Datum: Based on geoid models
 - Coordinate System

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3. Reference Systems - CRS

Aspect	TRS	CRS
Purpose	Global spatial framework for Earth's geometry.	Assign coordinates to map Earth's surface.
Components	Origin, orientation, scale, time evolution.	Datum + coordinate system (geographic/projected).
Dependency	Independent Earth model.	Relies on TRS for datum definitions.
Example	ITRF2020	WGS84/UTM (EPSG:32632)

The selection of Coordinate System leads to two types of CRS:

- Geographic Coordinate System (GCS)
- Projected Coordinate System (PCS)

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Topics

1. Geodesy
2. Earth's Shape and Models
3. Reference Systems (TRS)
4. CRS Types & Transformations
 - Geographic Coordinate System (GCS)
 - Projected Coordinate System (PCS)
 - Projection types
 - Projection distortions

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4. Geographic Coordinate System (GCS)

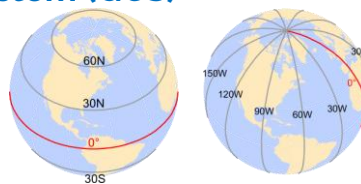
reference system for identifying locations on the curved surface of the earth



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4. Geographic Coordinate System (GCS)

- Uses latitude & longitude to define locations
 - Latitude: measures angular distance north/south of the equator
 - ranges from -90° (S) to 90° (N)
 - Longitude: measures angular distance east/west from the prime meridian (Greenwich)
 - ranges from -180° (W) to 180° (E)
 - Elevation: distance (positive or negative) to earth's surface



- Angle Units
 - Degree, minutes and decimal seconds
 - One degree has 60 minutes
 - One minute has 60 seconds

Example: 38° 20' 30.5"

Decimal degrees: $38 + (20/60) + (30.5/60 \times 60) = 38.34181^\circ$

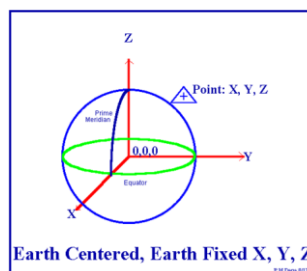
Radian: $2\pi \text{ rad} = 360^\circ \Leftrightarrow 1 \text{ rad} = \frac{360^\circ}{2\pi} \approx \frac{360^\circ}{2 \times 3.141593} \approx 57.29578^\circ$

Example: $38^\circ 20' 30.5'' \approx 38.34181^\circ \approx \frac{38.34181}{57.29578} \approx 0.669191 \text{ rad}$

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4. Geographic Coordinate System (GCS)

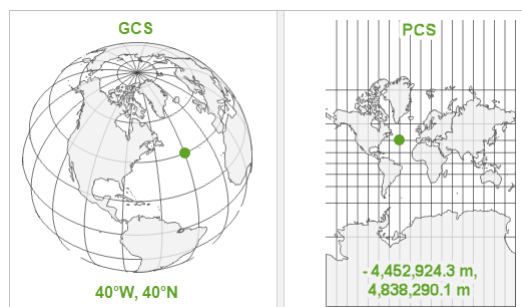
- Can also be expressed in Earth-Centered, Earth-Fixed (ECEF) Cartesian (X, Y, Z)
 - Geocentric – axes origin is close to the Earth's centre of mass
 - One axis is oriented according to the Earth rotation axis (the second and third axes are normal to the first one and to each other)
 - A point is defined by 3 coordinates (x, y, z)
 - Used in satellite-based positioning (GPS)



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4. Projected Coordinate System (PCS)

reference system that transforms earth from its curved shape (3D) to a planar shape (2D)



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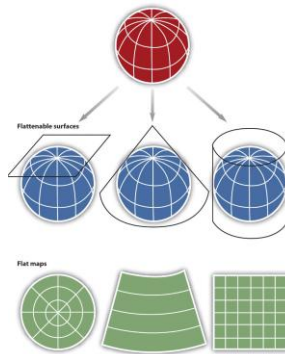
4. Projected Coordinate System (PCS)

- Systems that flatten Earth's surface using mathematical transformations, prioritizing specific spatial properties
- Allow precise location of points on a plane
- Minimizes distortion for local/regional mapping
- Consists of lines that intersect at right angles, forming a grid based on Cartesian coordinates
- Cartesian Coordinates are defined by:
 - 2 axes (typically x and y)
 - An origin where axis intercept
 - Linear unit of measurement

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4. Projected Coordinate System (PCS)

Going from a GCS to a PCS requires mathematical transformations, or projections



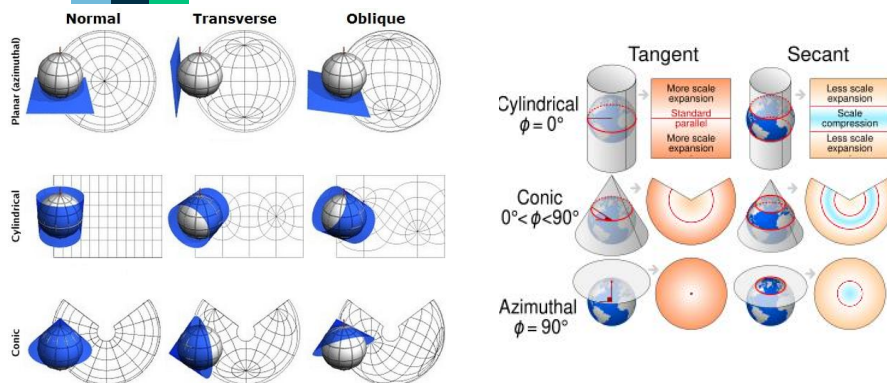
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4. Projection Types

- A mathematical function transforming ellipsoidal coordinates into coordinates of a plane (map coordinates)
- Most used projections require:
 - a flat surface or flattenable surface (cylinder, cone or plane) where the objects are projected
 - the position of this surface in relation to the reference ellipsoid
- The best projection for a map depends on the scale of the map and on the purposes for which it will be used

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4. Projection Types

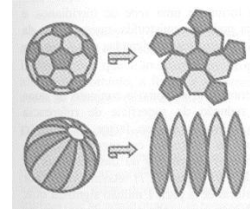


No projection preserves all properties – tradeoffs are inevitable.

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4. Projection Distortions

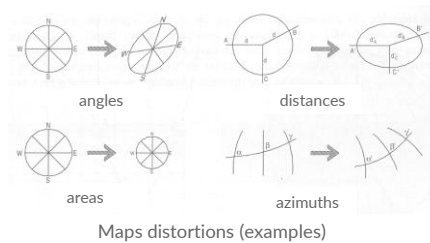
- Map projections are never absolutely accurate representations of the earth surface
- Ideally, maps should not contain distortions
- Maps should:
 - preserve relative positions of all locations (angles and shapes)
 - allow to measure distances and areas
 - allow to determine directions among geographic objects
- All projection methods involve at least one distortion type



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4. Projection Distortions

- The metric properties of each projection type allow us to understand which distortions can be avoided

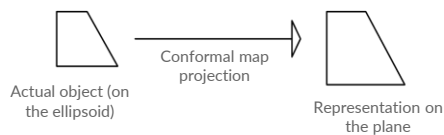


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4. Projection Distortions

- The metric properties of each projection type allow us to understand which distortions can be avoided

Conformal projections:
keep shapes (angles)



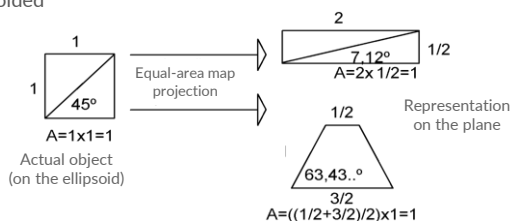
- Avoided distortions:
 - Conformal:** Avoids angular distortion

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4. Projection Distortions

- The metric properties of each projection type allow us to understand which distortions can be avoided

Equal-area projections:
keep areas



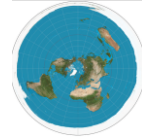
- Avoided distortions:
 - Conformal:** Avoids angular distortion
 - Equal-Area:** Avoids areal distortion

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4. Projection Distortions

- The metric properties of each projection type allow us to understand which distortions can be avoided

Azimuthal equidistant projections: keep distances along some (known) directions

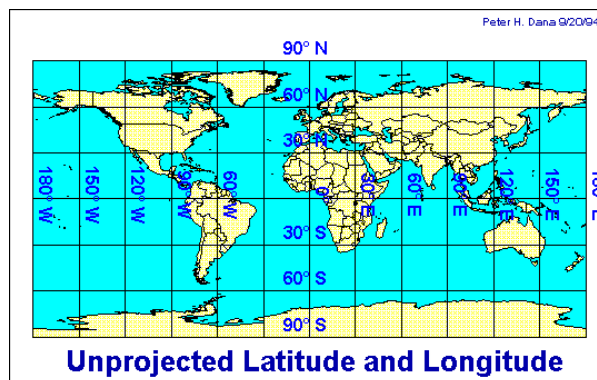


- Avoided distortions:
 - Conformal:** Avoids angular distortion
 - Equal-Area:** Avoids areal distortion
 - Equidistant:** Maintains true distances from a central point or along meridians/parallels
 - Azimuthal:** Preserves directions from a central point

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4. Projection Examples

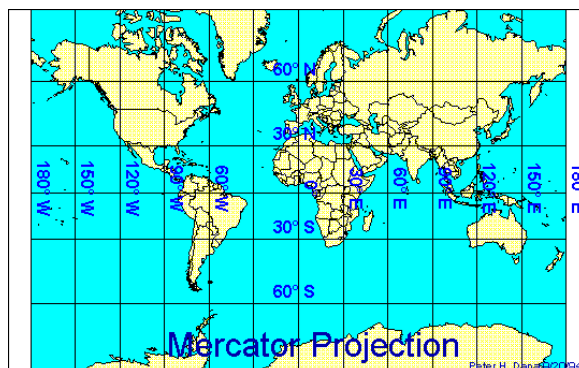
Unprojected flat representation



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4.Projection Examples

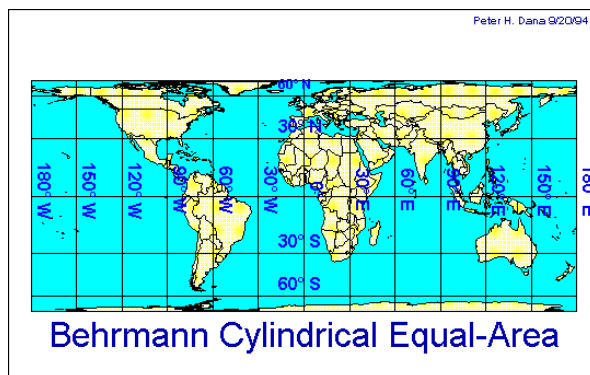
Conformal projection



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4.Projection Examples

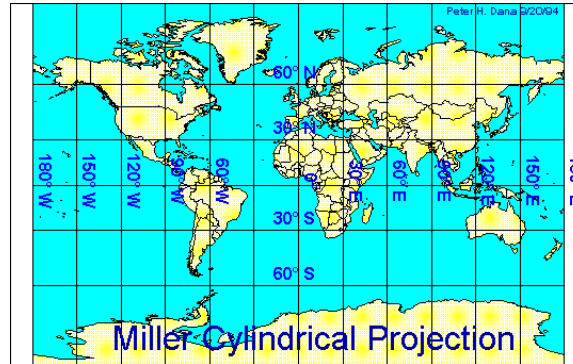
Equal-area projection



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4. Projection Examples

Non-conformal and non-equal-area projection



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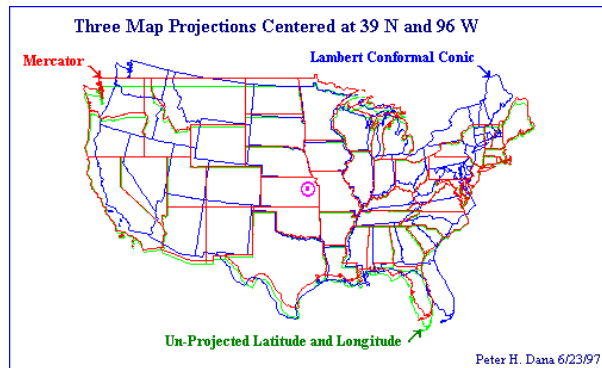
4. Projection Examples

https://en.wikipedia.org/wiki/List_of_map_projections

Projection	Images	Type	Properties	Creator	Year	Notes
Equiarectangular = equidistant cylindrical = rectangular = la carte parallélogrammatique		Cylindrical	Equidistant	Marinus of Tyre	c. 120	Simplest geometry; distances along meridians are conserved. Plate carrée: special case having the equator as the standard parallel.
Cassini = Cassini-Soldner		Cylindrical	Equidistant	César-François Cassini de Thury	1745	Transverse of equidistant projection; distances along central meridian are conserved. Distances perpendicular to central meridian are preserved.
Mercator = Weyl		Cylindrical	Conformal	Gerardus Mercator	1569	Lines of constant bearing (rhumb lines) are straight, aiding navigation. Areas inflate with latitude, becoming so extreme that the map cannot show the poles.

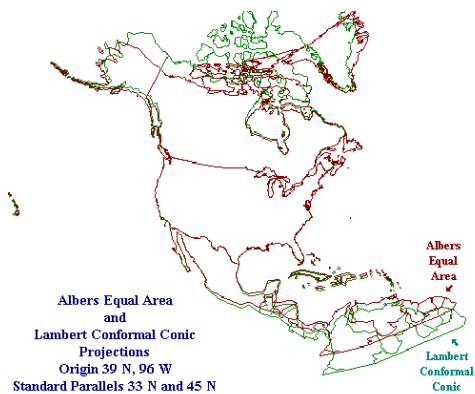
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4. Projection Differences



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4. Projection Differences



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Topics

1. Geodesy
2. Earth's Shape and Models
3. Reference Systems (TRS)
4. CRS Types & Transformations
5. CRS in GIS Software (QGIS/ArcGIS):

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Credits

The structure and content of the course, including most of the slides and exercises was developed by Professor Graça Abrantes (SIG 2021_2022) and Professor Rui Figueira (SIG 2023_2024)

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