

ISA

Geographic Information Systems 2026/2027

Lesson 11 - Coordinate Reference System in GIS software

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Topics

1. Geodesy

- Definition
- Objectives
- Core components

Category	Details
Definition	- From Greek: geo (Earth) + <i>daisia</i> (to divide/share)
	- Science of measuring and dividing Earth's surface
	- Involves Earth's shape , gravity field , and rotation
	- Definitions from IAG and NOAA highlight geometry, gravity, and temporal change
Objectives	- Extended to include other celestial bodies
	- Determine Earth's shape and size
	- Model gravity field (elevation, sea-level)
	- Understand rotation and orientation
Core Components	- Define reference systems for positioning
	- Monitor geodynamic phenomena : earthquakes, tectonics, glacial rebound
	- Enable satellite navigation and positioning
	- Support surveying, mapping, climate studies, and infrastructure development
Core Components	
► Earth Models	- Geoid: gravity-based mean sea level model
	- Ellipsoid: smooth mathematical surface (simplified Earth model)
	- Datum: aligns geoid and ellipsoid for location referencing
► Reference Systems	- Terrestrial Reference System (TRS): Earth-centered coordinate framework
	- Coordinate Reference System (CRS): includes datum and projection info
► Coordinate Systems	- Geographic Coordinate System (GCS): uses latitude and longitude
	- Projected Coordinate System (PCS): uses X, Y (and optionally Z) in flat space

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Topics

1. Geodesy

2. Earth's Shape and Models

- Ellipsoid
- Geoid
- Datum

Component / Concept	Definition & Description	Key Characteristics	Purpose / Use
Ellipsoid	A smooth, regular surface formed by rotating an ellipse around its minor axis to approximate Earth's shape.	- Defined by semi-major (equatorial) and semi-minor (polar) axes - Smooth, global-scale model - Ignores local terrain variations	- Used in Geographic Coordinate Systems (GCS) - Geometric base of many datums
Geoid	An irregular surface representing mean sea level, shaped by Earth's gravity variations.	- Equipotential surface (equal gravity potential everywhere) - Reflects mass distribution and gravity anomalies - Not a geometric shape (not sphere or ellipsoid)	- Used for vertical reference (e.g., elevation from MSL) - Standard model: EGM96
Datum	A model aligning the ellipsoid to the geoid to enable accurate positioning.	- Includes: Reference ellipsoid, geodetic center, prime meridian - Abstract coordinate system for Earth referencing	- Forms the framework for CRS - Basis for positioning, surveying, and mapping

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Topics

1. Geodesy

2. Earth's Shape and Models

- Ellipsoid
- Geoid
- Datum

Component / Concept	Definition & Description	Key Characteristics	Purpose / Use
Local Datum	A datum optimized to fit Earth's shape in a specific region.	- Minimizes distortion over a small area - May not align globally	- Used in older maps and region-specific applications
Global (Geocentric) Datum	A datum centered on Earth's center of mass, suitable for global use.	- Aligns well with geoid at global scale - Example: WGS84, ETRS89	- Used in GPS and international GIS datasets
Horizontal Datum	A datum prioritizing accurate surface location (lat/long).	- Applies to 2D planar positioning - Uses ellipsoidal surface	- Mapping and navigation on Earth's surface
Vertical Datum	A datum used to measure elevations or depths.	- Orthometric height (H): referenced to geoid - Ellipsoidal height (h): referenced to ellipsoid - Geoid height (N) = h - H	- Topography, sea-level monitoring, GPS elevation correction
Geodesic Point	A location precisely measured in relation to the ellipsoid.	- High-accuracy reference point - Used in building geodetic networks	- Surveying, mapping control points, and reference systems

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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)

Component	Definition & Description	Key Characteristics	Purpose / Use
Terrestrial Reference System (TRS)	A theoretical 3D reference framework that co-rotates with Earth to define spatial positions with high stability.	- Origin: Earth's center of mass - Orientation: Z-axis (rotation axis), X-axis (Greenwich meridian) - Scale Metric (SI units) - Time evolution: Accounts for tectonic drift (~2.5 cm/year) & tidal deformation	- Foundation for datums and geodetic positioning - Stable positioning over time for Earth observation & navigation
TRS Realizations (TRF)	Practical implementations of TRS at specific epochs.	- Defined by 7 transformation parameters - Examples: • ITRF: Global frame (e.g., ITRF2020) • WGS84: GPS standard • ETRS89: Europe-fixed, tectonic plate stable	- Used in GPS, satellite systems, and regional geodesy
Coordinate Reference System (CRS)	Practical system that translates TRS into coordinates to locate geographic data on Earth.	- Combines: • A Datum (horizontal and/or vertical) • A Coordinate System (GCS or PCS) - Links measurements to the Earth	- Basis for expressing GIS data coordinates - Enables mapping, analysis, and georeferencing
Geographic Coordinate System (GCS)	A type of CRS using angular coordinates (latitude & longitude) on a curved surface (ellipsoid).	- Angular units (degrees) - Based on a geodetic datum	- Used for global datasets, GPS, navigation
Projected Coordinate System (PCS)	A type of CRS using Cartesian coordinates (X, Y) to represent Earth's surface on a flat map.	- Linear units (meters) - Requires map projection	- Used for local/regional mapping and spatial analysis

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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

Component	Definition & Description	Key Characteristics	Purpose / Use
Geographic Coordinate System (GCS)	A CRS for identifying locations on Earth's curved surface using angular coordinates.	- Uses latitude, longitude, and optionally elevation - Units: degrees, minutes, seconds (or decimal degrees) - Can also be expressed in UTM Cartesian (X, Y, Z) - Used in GPS and global datasets	- Global navigation, satellite positioning, referencing curved Earth surface
Projected Coordinate System (PCS)	A CRS that transforms Earth's surface to a 2D map using projections.	- Based on Cartesian coordinates (X, Y) - Requires a projection method - Used for mapping on a plane - Distortion is minimized in local/regional areas	- Mapping, spatial analysis, local GIS operations
Projection	Mathematical transformation from GCS to PCS.	- Projects curved surface to a plane (cylinder, cone, plane) - Selection depends on scale and mapping purpose	- Enables flat map creation while controlling distortion
Projection Types	Categories of map projections based on preserved spatial properties.	- Conformal: Preserves shape/angles - Equal-Area: Preserves area - Equidistant: Preserves distances from a point/line - Azimuthal: Preserves direction from a central point	- Choose projection based on priority (e.g., navigation, area analysis)
Projection Distortions	All projections distort reality; none preserves all properties.	- Angles, areas, distances, and directions can be distorted - Tradeoffs are necessary	- Understand and choose projections that minimize the distortion most relevant to the map's purpose

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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):
 - Common CRS
 - "On the Fly" CRS Conversions
 - How to Set or Change the CRS in QGIS and ArcGIS

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4. CRS in GIS - Data in GIS

- **GDS**
 - spatial characteristics of geographic objects representing their location on the Earth surface
 - Points can be 2D (latitude & longitude; X & Y) or 3D (latitude, longitude & height; X, Y & Z)
 - Locations on the Earth surface are defined by **coordinates (numbers)** always referenced to a given **Coordinate Reference Systems (CRS)**
- **CRS is composed by:**
 - horizontal & vertical datums
 - coordinate system
 - projection (only when using a map coordinate system)
- **Standardization** (<http://spatialreference.org> - list of CRS in a number of formats)
 - EPSG (www.epsg.org) codes are defined by the Geomatics Committee of the International Association of Oil and Gas Producers (OGP), formerly European Petroleum Survey Group
 - The EPSG Geodetic Parameter Dataset is a structured repository of data required to:
 - define every CRS
 - transformations & conversions that allow coordinates to be changed from one CRS to another CRS

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4.CRS in GIS - Coordinate Transformations

- Coordinate transformations are needed for different purposes
- Spatial operations involving two or more input gds/layers usually require that all the input gds/layers have coordinates referenced to a common CRS
- To change a gds CRS, a new dataset must be created because all coordinate values must be recalculated
- If the gds CRS differ only on the projection, the coordinate conversion only needs to use the inverse projection and re-project
- If the gds CRS differ on the datums, the coordinate conversion (usually not error-free) needs:
 - either to do a direct lat/long conversion
 - or to convert lat/long into 3D Cartesian coordinates and perform a transformation of the (X,Y,Z) coordinates to the target CRS.

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4.CRS in GIS - Coordinate Transformations

- Most common transformations:
 - geodetic coordinates (lat, long):
 - Molodensky method – low number of parameters (low precision for large áreas)
 - Grid-based methods – use a dense set of points (grid) with known coordinates in both CRS & coordinate conversions are obtained by spatial interpolation (potentially the most accurate method)
 - 3D Cartesian coordinates (X, Y, Z):
 - Parameters are usually determined by a least-square method based on a known set of point coordinates in a given region
 - 3 parameter method – just a translation of the center of the ellipsoid (3 parameters, units: meters)
 - 7 parameter method – involves translation (3 parameters, units: meters), rotation (3 parameters, units: seconds) & change of scale (1 parameter, unit: parts per million – positive or negative)

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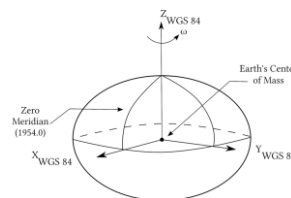
4. CRS in GIS - Common CRS

- WGS84
 - a global reference system (not projected)
 - used by GPS
- ETRS89
 - ETRS89 – Portugal TM06 (projected)
- UTM (projected and there are several ...)
- NAD83 (The North American Datum 1983)
 - geocentric datum that was established in 1986 for the United States, Canada, Mexico, Central America & the Caribbean Islands. Hawaii & Greenland were also connected to this datum.
 - tied to the North American Plate.

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4. CRS in GIS - WGS84 CRS

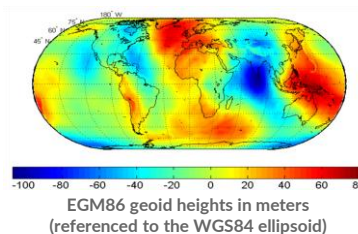
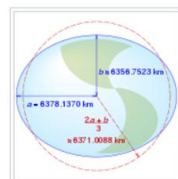
- The World Geodetic System (WGS) is a standard (EPSG: 4326) & comprises:
 - a 3-dimensional Cartesian coordinate system
 - a ellipsoidal reference surface (horizontal datum)
 - a geoid (vertical datum)
- 3D Cartesian coordinate system:
 - origin of the 3 axes: the Earth's center of mass
 - axis Z: the direction of the International Earth Rotation & Reference Systems Service (IERS) Reference Pole
 - axis X: the direction of the IERS International Reference Meridian & the plane passing through the origin & normal to the Z-axis
 - the IERS International Reference Meridian is 5.3 arc seconds ($\approx 0.00152^\circ \approx 102\text{m}$) east of the Greenwich Royal Observatory mark
 - axis Y: completes the orthogonal system



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4.CRS in GIS - WGS84 CRS

- Horizontal datum
 - WGS84 ellipsoid
 - semi-major axis (equatorial radius) $a = 6378137 \text{ m}$
 - semi-minor axis (polar radius) $b = 6356752.3142 \text{ m}$
 - flattening $f = (a-b)/a = 1/298.257223563 \approx 0.003352811$
 - differs from the standard geoid by at most 107m
- Vertical datum
 - WGS84 EGM96
 - definition involves 130676 parameters



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4.CRS in GIS - ETRS89 CRS

- The European Terrestrial Reference System 1989 (ETRS89) is the EU-recommended frame of reference for geodata for Europe
 - coordinates of Europe referenced to ETRS89 are not subject to change due to the continental drift
- ETRS89 comprises
 - a three-dimensional Cartesian coordinate system
 - prime Meridian: Greenwich
 - a ellipsoidal reference surface (horizontal datum ETRS89)
 - GRS 1980: semi-major axis $a = 6378137\text{m}$
 - semi-minor axis $b = 6356752.314140\text{m}$
 - flattening $f = 1/298.257222101$
- ETRS89 - Portugal TM06 (EPSG: 3763) (**best fits Portugal onshore**)
 - based on the ETRS89 system projected using a Transverse Mercator projection
 - Origin of the axes: latitude $39^\circ 40' 05''$, 73 N and longitude $08^\circ 07' 59''$, 19 W
 - Unit: meter

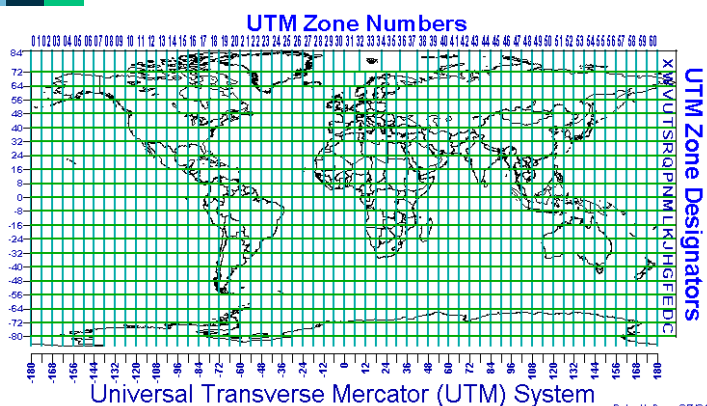
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4. CRS in GIS - UTM CRS

- The Universal Transverse Mercator (UTM) system is not a single crs, this system divides the Earth into a grid:
 - Earth is divided into 60 zones, each being 6° of longitude, & uses a secant transverse Mercator projection in each zone
 - Zone 1 covers longitude 180° to 174° W; zone numbering increases eastward to zone 60 – the polar regions south of 80°S and north of 84°N are excluded
 - Each zone is segmented into 20 latitude bands, each being 8° high.
 - latitude bands are lettered starting from "C" at 80°S, increasing up the English alphabet until "X", omitting the letters "I" and "O" (because of their similarity to the numerals 1 & 0)
 - last latitude band, "X", is extended an extra 4 degrees, so it ends at 84°N latitude, thus covering the northernmost land on Earth
 - Horizontal datum
 - WGS84 ellipsoid is now generally used to model the Earth in the UTM coordinate system
 - For different geographic regions, other datum systems (e.g.: ED50, NAD83) can be used

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4. CRS in GIS - UTM CRS



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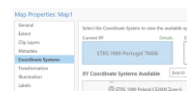
4. CRS in GIS - CRS in GIS platforms

- GIS software has the capability of converting coordinates from one reference system to another provided conversion rules are present.

- A project/map has always a given CRS
 - It is the so-called map CRS



QGIS



ArcGIS Pro

- The gds / layers used in GIS projects always use a given CRS
 - Use the layer Properties -> Source to know the layer CRS (EPSG code and name)
- These gds CRS may be different among them (and often they are)
- The gds CRS and the map's CRS may also be different

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4. CRS in GIS - “on the fly” conversions

- Good quality simultaneous visualization of spatial data referenced to different CRS is possible because GIS platforms computes “on the fly” conversions
 - QGIS/ArcGIS compute “on the fly” conversions from every layer CRS to the map's CRS provided conversion rules are present
 - Therefore, visualization always uses the map's CRS

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4. CRS in GIS - Changing the CRS in QGIS/ArcGIS

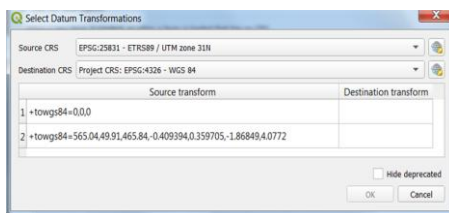
- It is possible to change a QGIS/ArcGIS **map CRS** to a different CRS using the context menu:
 - QGIS: Project → Properties → CRS window
 - ArcGIS: Map → Properties → Coordinate Systems
- In QGIS/ArcGIS, it is possible to change a **gds CRS** (executing required coordinate conversions) using the function Data → Export features
 - choose a CRS for the output gds different from the input gds CRS
- Using the context menu (QGIS) or tool Define Projection (ArcGIS), it is possible to set CRS of the layer. This does not convert the coordinate values:
 - this function is only intended to overcome unexpected situations such as a gds lacking its CRS (and provided that we know it)

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4. CRS in GIS - PROJ.4 projection library

QGIS uses the **PROJ.4** projection library for CRS transformations

Example:

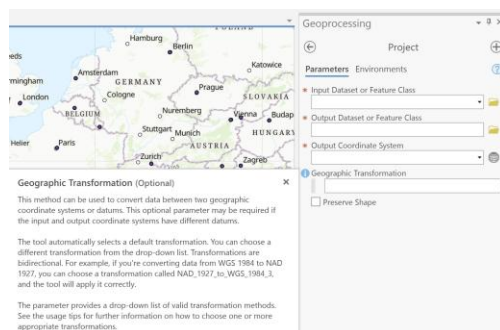


More information at <https://proj4.org/>

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4.CRS in GIS - ArcGIS Project tool

ArcGIS can perform CRS transformations with the tool Project (Data Management Tools)



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4.CRS in GIS - Scale & Resolution

- Scale & resolution are concepts related to map representations, yet impacted by CRS selection
- **Scale:**
 - Property of a map
 - ratio of a distance on the map to the corresponding distance on the ground
- **Resolution:**
 - level of detail in spatial data, indicating how finely geographic features are represented
- A map always includes a scale
 - ex: 1:10000
 - scale is a number without unit
 - and often a graphical or bar scale
- Scale 1:100 is larger than scale 1:10000
- Scale 1:250000 is smaller than scale 1:50000



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4. CRS in GIS - Scale & Resolution

- The scale is described by the extent & detail of a geographic information element
 - Extent: area/region contained in a geographic information element
 - Detail: smallest observable portion of a piece of geographic information



1:25000



1:500000

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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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