Coordinate Systems and Map Projections
Introduction

“Every map user and maker should have a basic understanding of projections and coordinate systems no matter how much computers seem to have automated the process.”

- Creating spatial data (collecting GPS data)
- Import into GIS and overlay with other layers
- Acquiring spatial data from multiple sources
- Display your GPS data using maps
Introduction

- Coordinate system: reference system for geographic location → Georeferencing

- There are 2 types of coordinate systems:
  - **Geographic Coordinate Systems** (unprojected)
    - A reference system using latitude and longitude to define the location of points on the surface of a sphere/spheroid/geoid
  - **Projected Coordinate Systems**
    - A map projection is the systematic transformation of locations on the earth (latitude/longitude) to planar coordinates
Georeferencing with coordinates

- Longitude $\lambda$ and latitude $\phi$
  - Angle from equator: latitude $\phi$
  - Angle east of Greenwich: longitude $\lambda$

- Coordinate systems are based on agreements

- Coordinates relative to a „model“ of the earth
  - Spherical, unprojected coordinate system
  - Angular coordinates are perfectly suited to the spherical surface of the Earth
Latitude and Longitude

- Coordinates are expressed in degrees, minutes and seconds (and variations of that).
- Position coordinates are based on an angular distance from a known reference point.
- In WGS-84, that reference point is where the Prime Meridian and Equator intersect.
- WGS-84 Latitude/Longitude is perhaps the predominant coordinate system used in GIS.
Latitude and Longitude

- Prime Meridian
- (Longitude)
- Equator
- (Latitude)
- Point of Origin
Latitude and Longitude

- Prime Meridian
- Equator
- N
- S
- 0º, 0º
- W 30º 20º 10º
- E 10º 20º 30º
Latitude

- Latitude is comprised of parallels, which are circles around the earth paralleling the equator.

- Parallels are rays that originate at the center of the earth. They are designated by their angle north or south of the equator.

- The equator is 0° latitude, and the north and south poles are at 90° angles from the equator.

- The linear distance between parallel lines never changes, regardless of their position on Earth. That distance is approximately 111 kilometers per degree, anywhere on Earth.
Parallels of Latitude

10°
Parallels of Latitude

- 20°N
- 10°N
- 0°N
- 10°S

10° 1110 kilometers
Longitude

- Longitude is comprised of meridians that form one-half of a circle, or plane.
- Meridians are rays originating at the center of the earth.
- Meridians are designated by their angle west or east of the prime meridian.
- The prime meridian is designated 0º and extends from the north pole to the south pole through Greenwich, England.
- **Meridians are angled, and do not parallel each other.**
- The linear distance between one degree of longitude at the equator is approximately 111 kilometers.
- The linear distance between one degree of longitude at the arctic circle is about 41.84 kilometers.
Meridians of Longitude
Meridians of Longitude

- 10º
- 386 Km
- 10º
- 740 Km
- 10º
- 1110 Km

120º W
110º W
Determining Latitude and Longitude

- **30°N, 50°W**
- **Equator (0°)**
- **Prime Meridian (0°)**

- **50°**
- **W**
- **30°N**
Geographic Coordinate System

- Usually a universal coordinate System (lat/lon)

- Lat/lon good for locating positions on surface of a globe

- **Lat/lon not efficient for measuring distances and areas!**
  
  - Latitude and longitude are not uniform units of measure
  
  - One degree of longitude at equator = 111.321 km (WGS-84)
  
  - One degree of longitude at 60° latitude = 55.802 km (WGS-84)
Great Circle Distance

- On a sphere the shortest path between two points is given by the great circle distance.
- An arc linking two points on a sphere.

- The Great Circle Distance (D) on a sphere:
  
  - \( \cos D = (\sin a \sin b) + (\cos a \cos b \cos |c|) \)
  
  - \( a \) and \( b \) are the latitudes of the respective coordinates
  
  - \( |c| \) is the absolute value of the difference of longitude between the respective coordinates.
The Great Circle Distance between New York and Moscow

- New York: 40°45’N 73°59’W
- Moscow: 55°45’N 37°36’E

Cos (D) = (Sin a Sin b) + (Cos a Cos b Cos |c|)

- Sin a = Sin (40.5) = 0.649
- Sin b = Sin (55.5) = 0.824
- Cos a = Cos (40.5) = 0.760
- Cos b = Cos (55.5) = 0.566
- Cos c = Cos (73.66 + 37.4) = -0.359
- Cos (D) = 0.535 – 0.154 = 0.381
- D = 67.631 degrees
- 1 degree = 111.32 km, so D = 7528.66 km
The shape of the earth

- From sphere to an ellipsoid of rotation (spheroid)
  - Polar flattening. Meridians are ellipses → ellipsoid of rotation (spheroid).
  - Ellipticity $f$ of WGS-84: $f = \frac{(a - b)}{a} \approx 1/298$
  - $a$ is the distance from the spheroid center to the equator and $b$ the distance from the center to the pole

- Problems due to gravitation field
  - Ellipsoid of rotation is not an exact iso-surface of gravitation; therefore, there is a deviation between coordinates from triangulation and astronomically (GPS) determined coordinates
The shape of the earth

- the geoid: the „true“ shape of the earth
  - Due to irregular distribution of masses within the Earth, the geoid is irregular
  - Geoid is only approximated ellipsoid of rotation
  - Local fit of ellipsoids
Ellipsoid & Geoid

- Topographic Surface
- Ellipsoid (GPS)
- Geoid
- Earth
Geodetic reference systems

- **Geodetic Reference System**: set of all theoretical conventions to define a coordinate system for geodetic purposes. Reference surface (ellipsoid + rules for handling geodetic measurements).

- **Datum**: set of parameters defining a coordinate system, and a set of control points whose geometric relationships are known, either through measurement or calculation: origin, direction of axis, reference point for elevations.
Importance of Datum

- A datum specifies the earth-model (ellipsoid), and the origin associated with a particular set of coordinates.

- Datums provide the link between the earth and coordinate systems.

- Without a datum, coordinates have no meaning.

- There are many datums used worldwide.
Geodetic reference systems

- **Reference network**: geodetic implementation of reference system. Computation of coordinates and heights of given points by means of geodetic surveys.

- Usually „grown“ over long time → **not free of contradiction**.

- Unique conversion between coordinate systems, e.g. GPS, to e.g., national geodetic coordinate systems not possible. Fit by reference points into **reference network**.

- Many available software implementations.
Map projections

- Properties of map projections
- Projection types (class)
- Aspect
- Naming of projections
- Choice of appropriate projection
- Examples of important projections
What are Maps

- A map is a two-dimensional representation of the Earth’s surface.
- Maps incorporate projections and datums for increased accuracy.
- All maps distort the earth to some extent.
- When using a map with a GPS receiver, the datum and coordinate system must match.
Properties of map projections

- Conformal projections
  - Preserve local shape → grid of intersecting lines of latitude/longitude on globe are perpendicular (preserve angles)

- Equal-area projections
  - Preserve area of features → angle and/or scale may be distorted

- Equidistant projections
  - Preserve distances between certain points; scale is not maintained correctly on an entire map

- True-direction projections
  - True-direction or azimuthal projections map great-circles through the center point as straight lines
Type of projection

- Projection onto geometric surfaces (plane, cone, cylinder), which can be flattened by unrolling.
- Mathematical expressions preserving desired properties.
Type: Conic projections

- Tangent at standard parallel

- Secant conic projections (2 parallels)
Type: Cylindrical projections

- Tangent or secant
- Mercator projection, touches at equator
- Transverse Mercator projection touches at meridian
Planar (azimuthal) projections

- Tangent or secant
- Polar, equatorial or oblique
Classification according to aspect

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Naming of projections

- Identified by giving:
  - class, aspect, property.

- Specific properties:
  - name of originator,
  - nature of any modifications.

- E.g. topographic overview map 1:500,000: normal secant conformal conic projection (LAMBERT) with standard parallels 46° W and 49° N latitude
Selecting a suitable projection

Considerations

- How can results be best presented on a map?
- For analysis in GIS, all maps must have a common reference
- To be able to quantify areas, lengths, etc. the respective accuracy must be determined

Rules of thumb

- Errors and distortions increase from the origin of the projection towards its edges
- In tropical areas → cylindrical projections
- In temperate latitudes → conic projections
- Polar regions → planar (azimuthal) projections
Important map projections

- **Mercator Projection**
  - Cylindrical projection
  - Spacing of parallels increases toward poles, but slowly.
  - North-south scale increases at the same rate as the east-west scale: scale is the same around any point.
  - Conformal: meridians and parallels cross at right angles.

- Straight lines represent lines of constant compass direction:
Important map projections

- UTM (Universal Transverse Mercator) System
  - Version of transverse Mercator projection.
  - For cartography between 84° N and 80° S.
  - Great for small areas
  - Uses a GRID system (Earth divided into 60 zones)

- Coordinates expressed in meters!
UTM Grid: 60 Zones, and 20 Latitude Bands
Important map projections

- **WGS-84 planar representation (cylindrical)**
  - Measurements by GPS (Global Positioning System)
  - Approximate conversion of GPS coordinates into national system using local parameters; fit into national system by reference points

\[
\begin{align*}
\mathbf{v}_x & = -577,326 \text{ m} \pm 0,92 \text{ m} \\
\mathbf{v}_y & = -90,129 \text{ m} \pm 0,80 \text{ m} \\
\mathbf{v}_z & = -463,919 \text{ m} \pm 0,94 \text{ m} \\
\mathbf{d}_m & = -2,4232 \text{ ppm} \pm 0,09 \text{ ppm} \\
\mathbf{R}_x & = 15,8537 \text{ cc} \pm 0,08 \text{ cc} \\
\mathbf{R}_y & = 4,5500 \text{ cc} \pm 0,12 \text{ cc} \\
\mathbf{R}_z & = 16,3489 \text{ cc} \pm 0,06 \text{ cc} \\
\mathbf{X}_{\text{MGI}} & = \mathbf{v} + (1 + \mathbf{d}_m) \mathbf{R} \mathbf{X}_{\text{WGS}}
\end{align*}
\]
Important map projections

- Lambert conformal conic projection
  - Used frequently for overview maps
  - Two reference parallels secant to the globe
  - No distortion along the standard parallels
  - Conformal projection