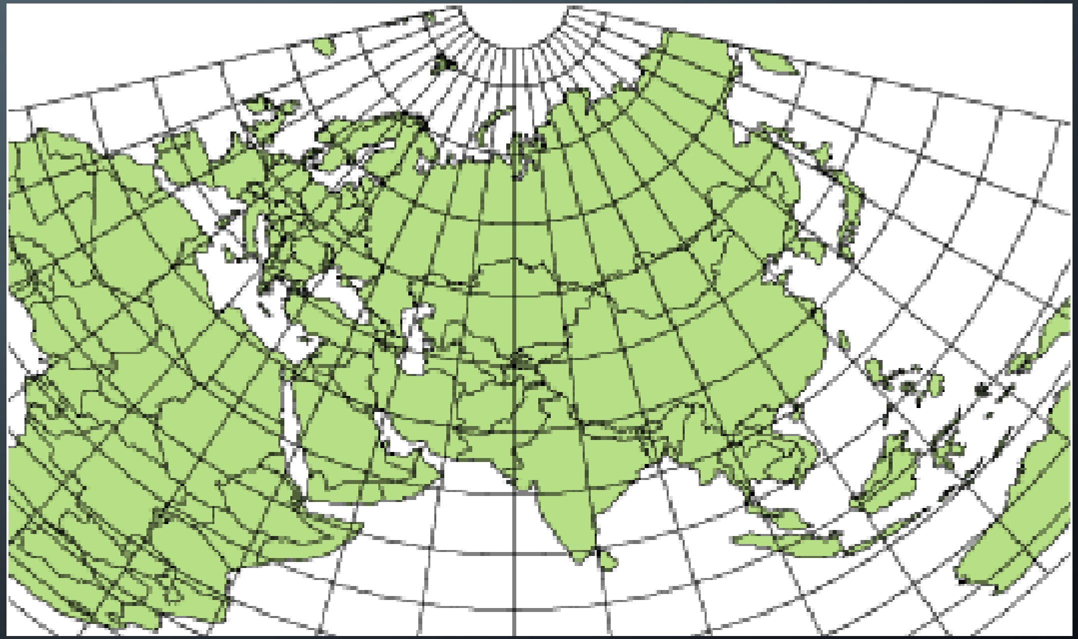
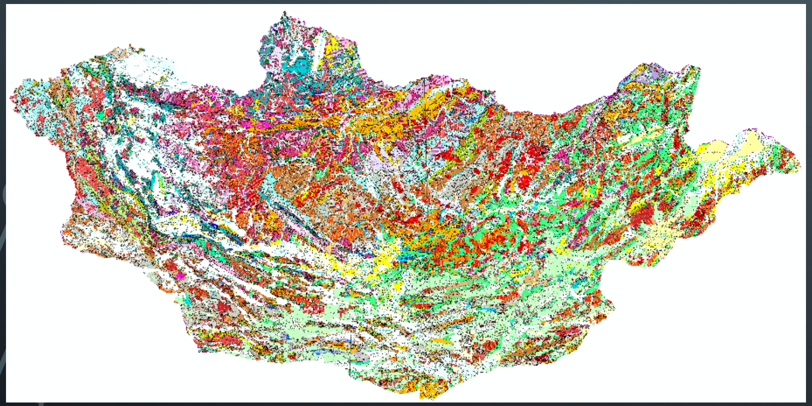
COORDINATE SYSTEMS AND MAP PROJECTIONS

AN INTRODUCTION



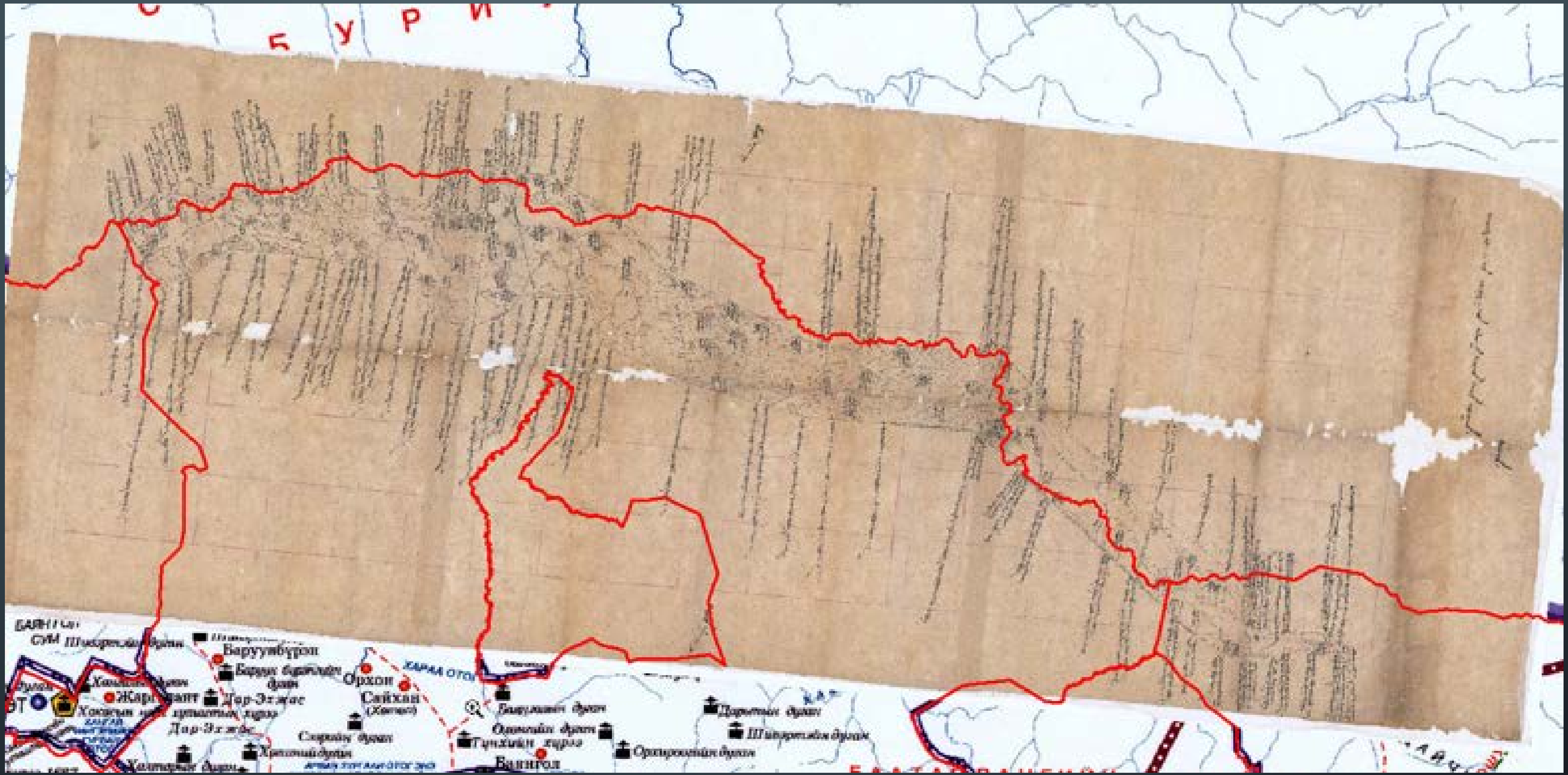


WHY MAPS?

- The first map was probably created over 8000 years ago (Çatalhöyük, Turkey):

- Purpose of early maps: navigation and orientation, later also military purposes
- 18th century: cadastre maps requiring higher accuracy (Gauß!)
- Today wide spectrum of applications:
  - Topographic maps
  - Thematic maps
  - Navigation system maps
  - Web maps

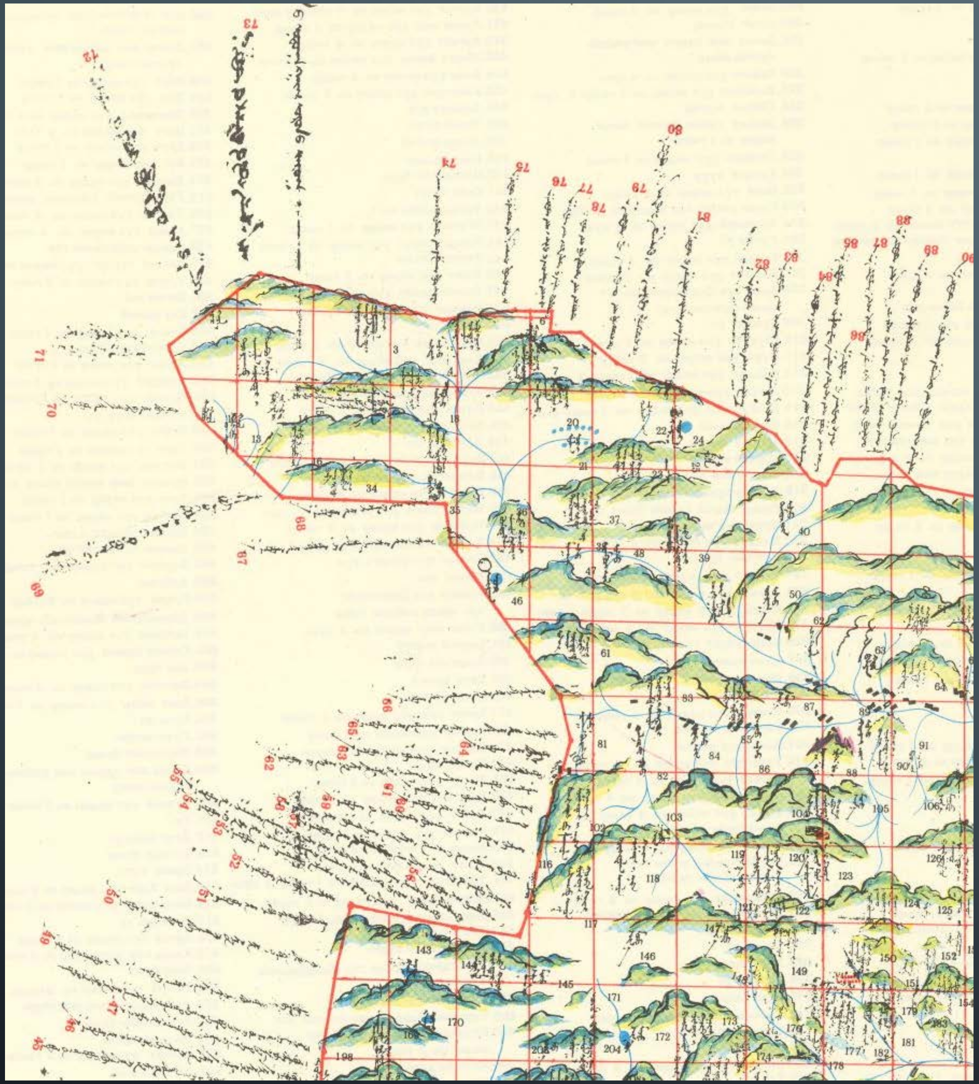
WHY MAPS?



Mongolian northern border, 19th century: defence.

Background and red boundary line from modern maps. Note the accuracy!

WHY MAPS?



Tusheet Khan Map, Mongolia, early 19th century: strategic regional planning

WHY COORDINATE SYSTEMS?

- Unambiguous description of a location in space
- Description uses numbers; required quantity of numbers depends on the dimensionality:
  - 1 dimension: 1 number x (e.g. position along a railway)
  - 2 dimensions: 2 numbers x/y (e.g. position on a map)
  - 3 dimensions: 3 numbers x/y/z (e.g. position of an aircraft)

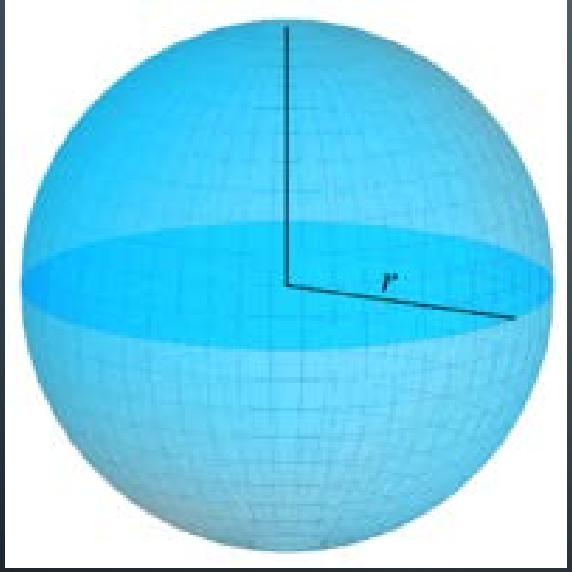
- Ptolemy applied coordinate systems to maps (2nd century)
- Increasingly important for cadaster maps (Gauß, 19th century)

THE FLAT EARTH

- In ancient times, generally people believed the world was flat
- This is “nearly true” for very small areas
- Mapping of a flat world would be very easy
- Only 2 dimensions would need to be considered

THE ROUND EARTH MODEL

- Since centuries, the earth has been commonly perceived as a sphere, a perfectly round geometrical object which can be easily described by:
  - The location of the centre
  - The constant radius

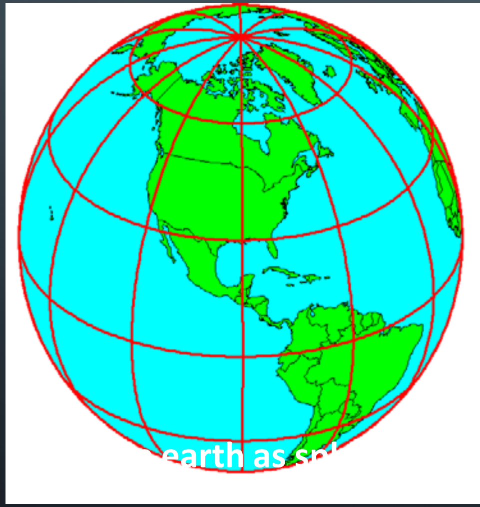


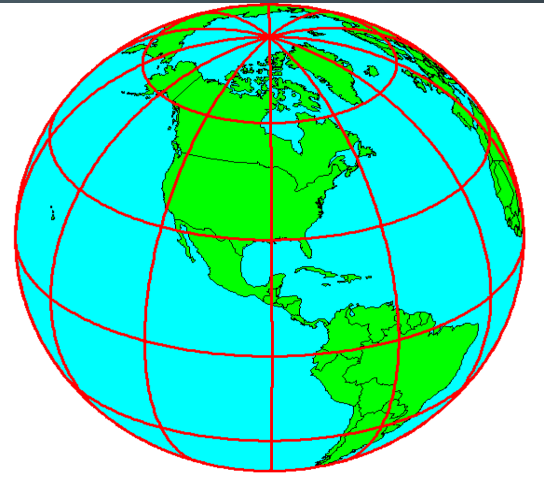
A sphere

World map, Amsterdam 1689

THE ELLIPTICAL EARTH MODEL

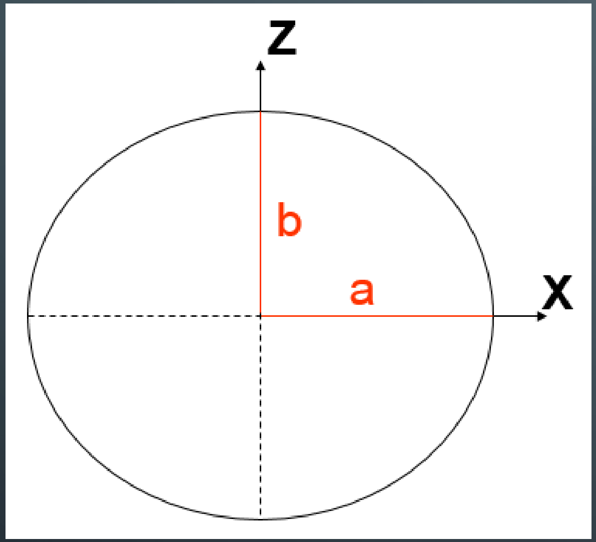
- Due to its rotation, the earth is not a sphere but a *spheroid*, an object similar to a sphere (like a perfect ball) but not a true sphere
- Radius:
  - Equatorial radius: 6378.1 km
  - Polar radius: 6356.8 km



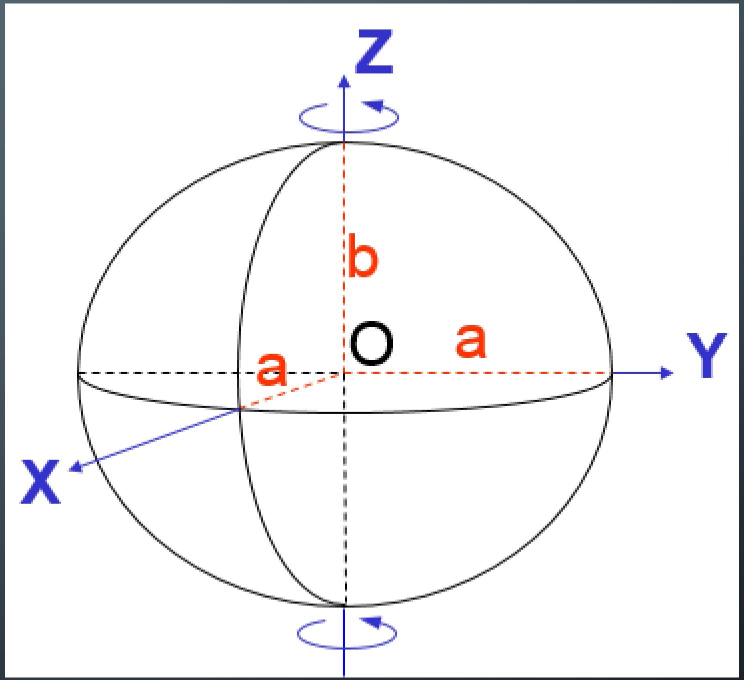


THE ELLIPTICAL EARTH MODEL

- The shape of the earth can be approximated as an ellipsoid, a three-dimensional rotating ellipse



Ellipse



Ellipsoid of revolution = spheroid

THE ELLIPTICAL EARTH MODEL

- The definition of an ellipse to describe the earth's shape requires an exact measurement of:
  - The major (equatorial) axis (a)
  - The minor (polar) axis (b)

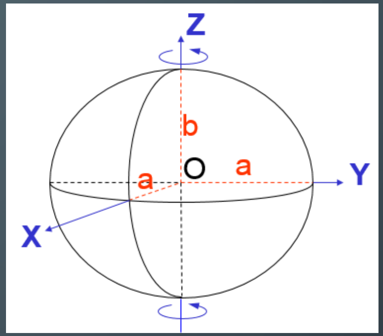
  The ratio between these two values is called *flattening*
- In times before satellite navigation, calculating the axes of the earth was extremely difficult
- In different countries, different values were introduced and established, known as the following ellipsoids:
  - Krassovski 1940 (Soviet Union, Mongolia)
  - Clarke 1866 (USA)
  - Bessel 1841 (Europe, Japan)
  - Plus many others….

THE ELLIPTICAL EARTH MODEL

- Today's standards are:
  - GRS-80 (Geodetic Reference System 1980)
  - WGS-84 (World Geodetic System 1984)
- Both were calculated mainly based on satellite measurements
- WGS-84 can be seen as a slightly adjusted GRS-80; there is not much difference

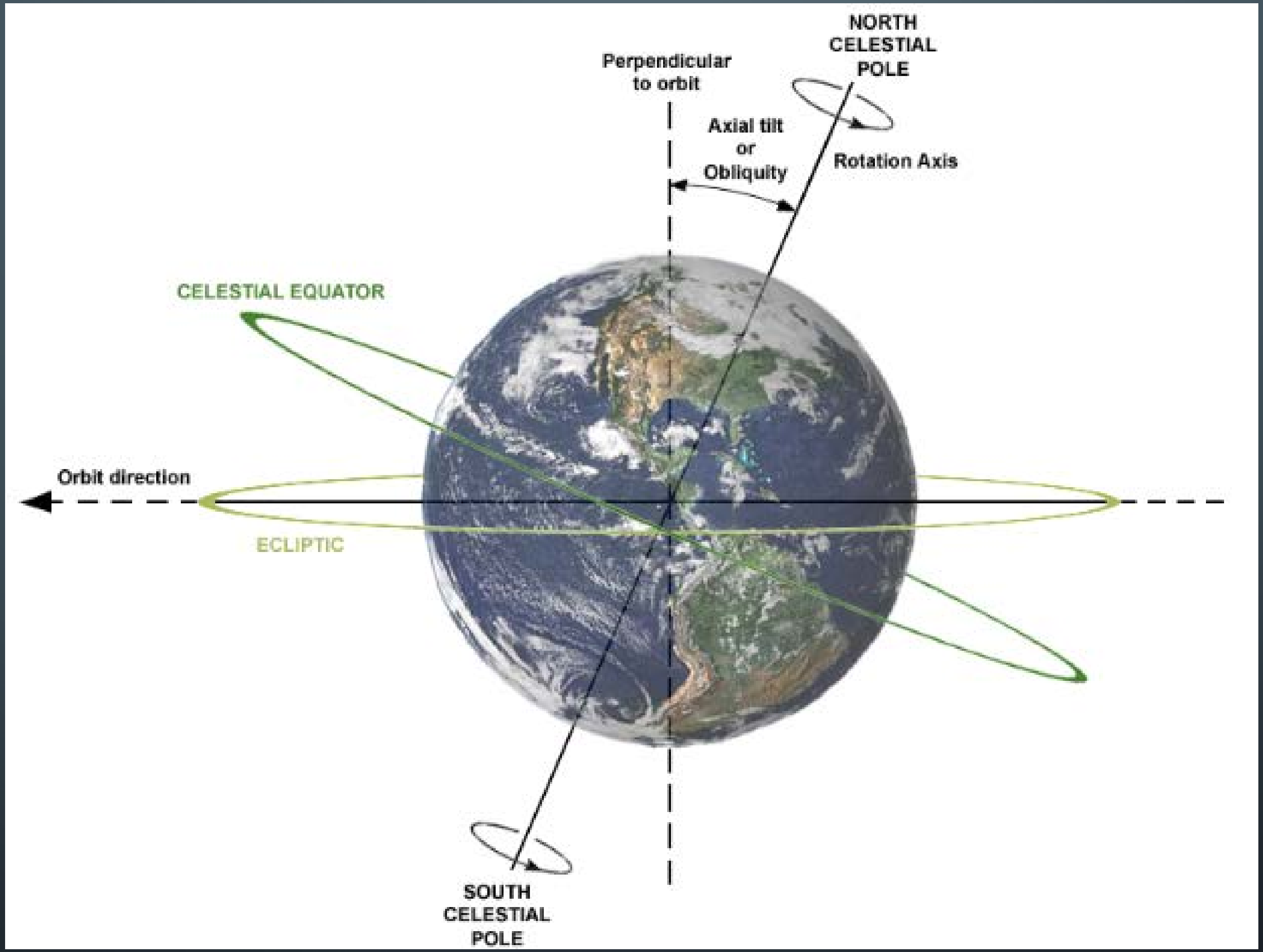
REFERENCE FRAME

- For establishing a global coordinate system, a *reference frame* (also referred to as *rotational axis*) needs to be defined, through defining:
  - Position of the north pole
  - Position of the south pole
  - Position of the centre of the earth



- In practice a *realization* of the reference frame is required using fixed benchmarks whose location is frequently surveyed
- This can be done by through:
  - GPS
  - Satellite laser ranging to the earth's surface
  - Measuring signals of very far astronomical objects (quasars) simultaneously at different positions of the earth's surface (*very long range interferometry*)

REFERENCE FRAME



Rotation of the earth

DATUMS

- Global coordinate systems are based on datums:

  Ellipsoid + Axis of rotation (or: reference frame) = Datum

- Different datums were introduced in different parts of the world, adapting well to countries or regions:
  - Pulkovo 1942 based on the Krassovski 1940 ellipsoid (Soviet Union, Mongolia)
  - NAD 1927 based on the Clarke 1866 ellipsoid (USA)
  - Potsdam based on Bessel 1841 (Germany)
- Today the most commonly used Datums are:

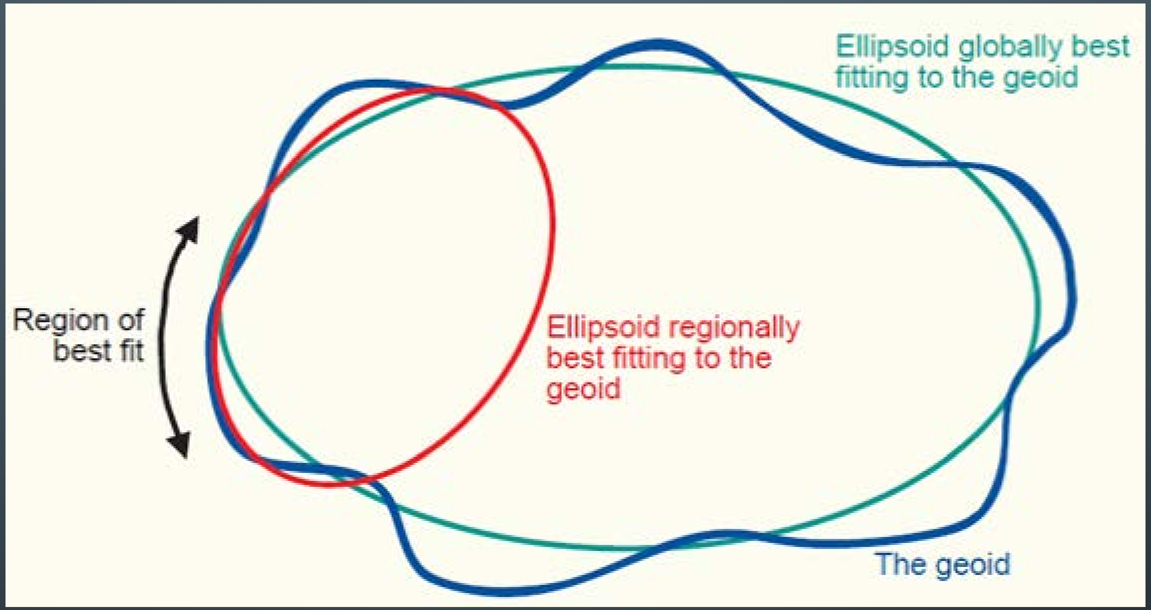
Base ellipsoid	Datum	Computed by
GRS-80	International Terrestrial Reference Frame (ITRF) 20xx	International Association of Geodesy
WGS-84	WGS-84	US Defence

- Difference ITRF2000 – WGS-84: < 1 cm

THE IMPERFECT SHAPE OF THE EARTH

- To make it more complex: the earth's shape is not a geometrically perfect ellipsoid
- Local datums can describe the shape of the earth for a specific region better than global models
- A global datum is required for many good reasons, such as:
  - Definition of state boundaries
  - Usage of GPS
  - Air traffic
  - Small scale maps showing large regions
- Locally, a global datum might not be as accurate as local datums
- WGS-84 has been established as global model and is an ellipsoid AND a datum
- ITRF is frequently updated (ca. every 2 years) to account for tectonic movements

THE IMPERFECT SHAPE OF THE EARTH



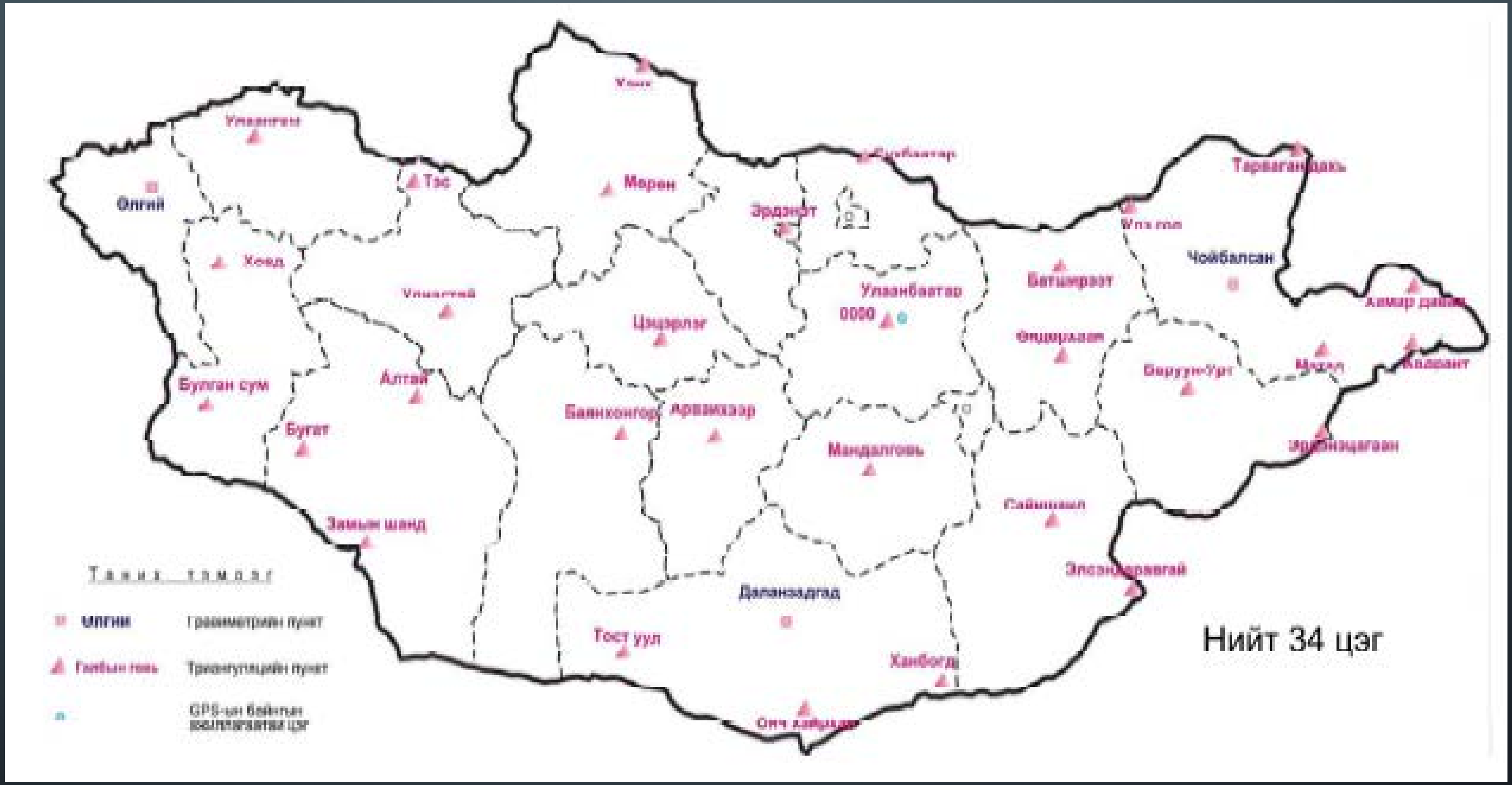
A globally best fitting and a regionally best fitting ellipsoid (shapes exaggerated)

GEODETIC REFERENCE SYSTEMS

- Before satellite navigation, geodetic surveys were extremely difficult and time consuming
- Basis for surveys: control network
  - Geodetic control points
  - First order control points should provide highest accuracy
  - Monumented benchmarks

- Surveys were performed starting from control points and using triangulations of lines of sight distances and bearings
- The control network forms the geodetic reference system
- In theory, the geodetic reference system applies the previously described datums to practice
- In practice, the geodetic reference system (previously) used in Mongolia does not 100% follow the Pulkovo 1942 datum definition

GEODETIC REFERENCE SYSTEMS



Mongolian first order control point network

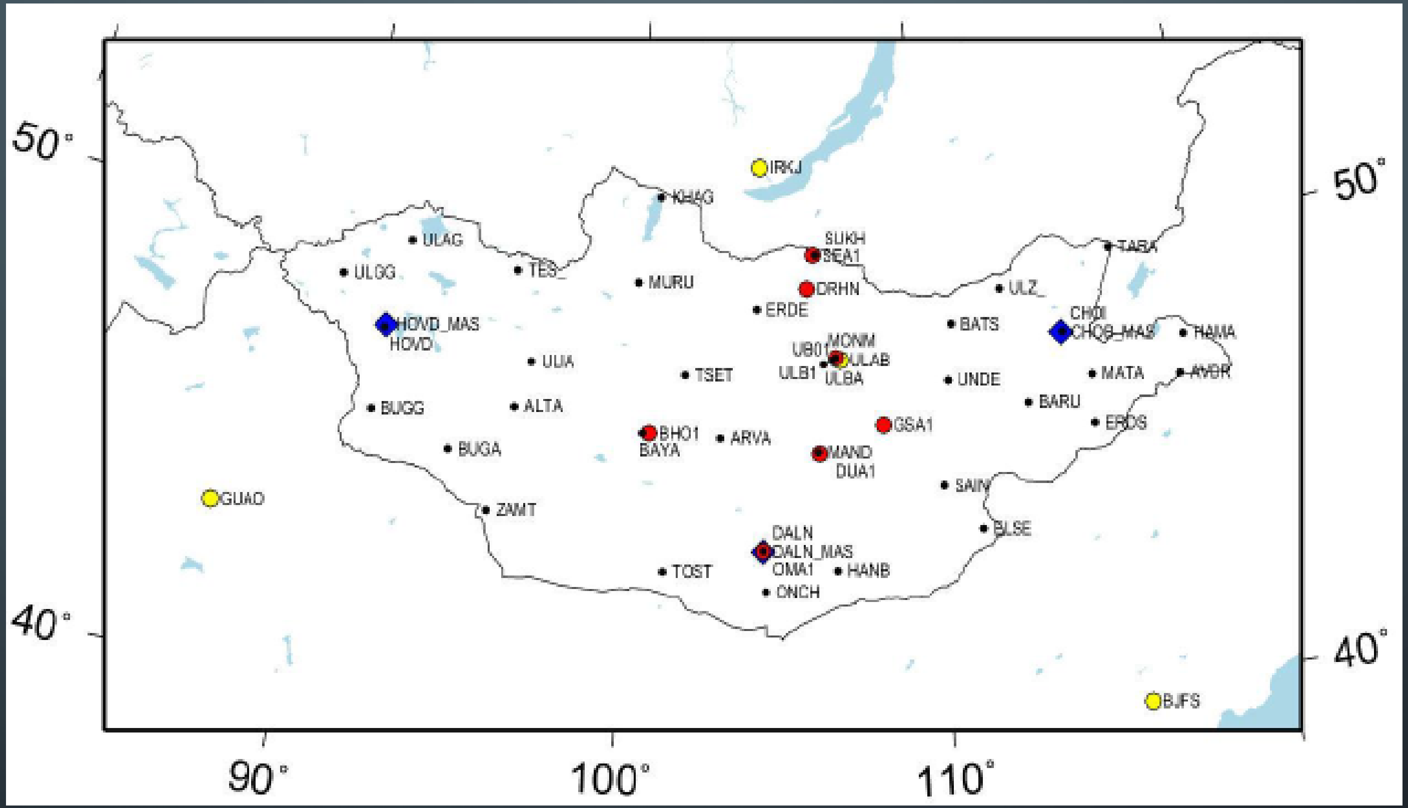
GEODETIC REFERENCE SYSTEMS

- For very small areas (construction site, mining site, city), local geodetic reference systems have been used
- They can provide good accuracy for that area, but are not compatible with other local geodetic reference systems
- Tasks like implementing and managing a nationwide mining or land cadastre require usage of a common reference system
- Since 2009.05.01, the official reference system of Mongolia is WGS-84 (ellipsoid and datum), replacing Krasovski 1940 (ellipsoid) and Pulkovo 1942 (datum)
- Cadaster systems and maps MUST use it
- Maps and data MUST indicate the reference system they are using

GEODETIC REFERENCE SYSTEMS

- MONREF97 is a geodetic reference system
- It is the physical local implementation of ITRF with the ellipsoid GRS-80 through passive geodetic reference points
- Using one of the 35 control points of MONREF97 as position for a GPS base station, highly accurate fields surveys can be carried out
- This physical implementation was extremely correct in August 1997 (that's why it is called MONREF97), but for the previously mentioned reasons, accuracy decreases year by year
- Meanwhile, an update has been made, MONREF2014, with differences of a few cm to MONREF97 (ca. 5 cm on average)

GEODETIC REFERENCE SYSTEMS



MONREF97 / 2014 control point network (35 points)

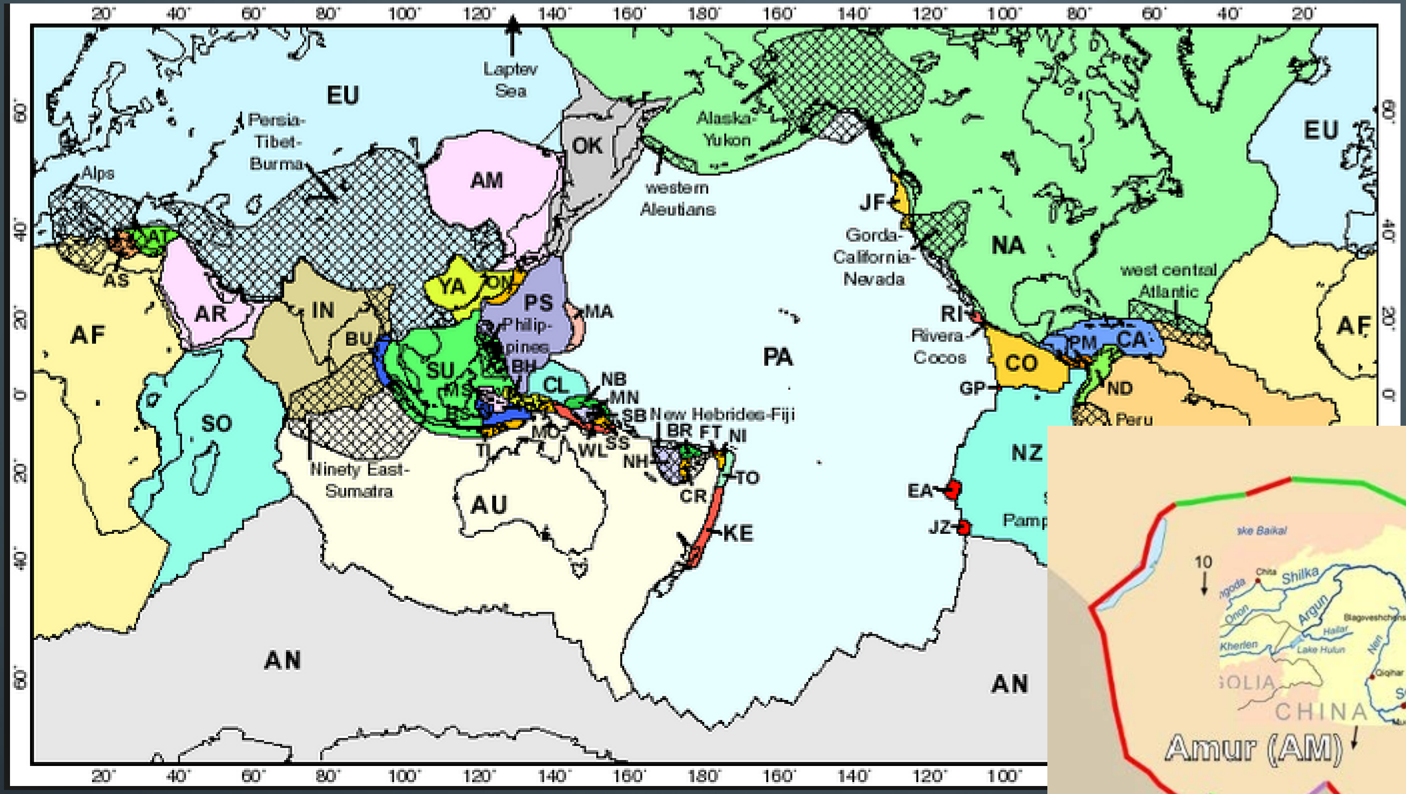
THE EARTH IN MOTION

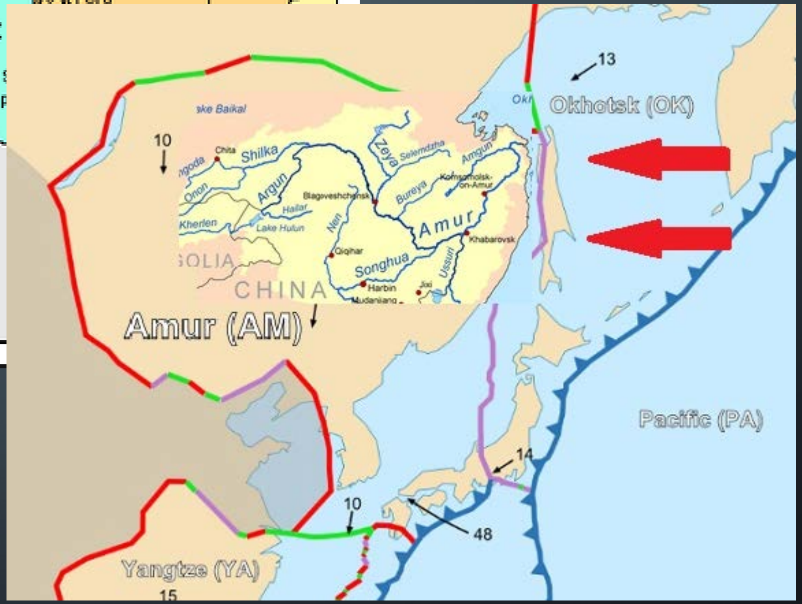
- Regardless of the ellipsoid and the reference frame, landmasses are moving in relation to each other and in relation to the reference frame:
  - Plate tectonics: plates move at speeds of 1 mm – 16 cm per year
  - Earthquakes can move parts of the surface up to 1 m within a few minutes
- Think of the ellipsoid and reference frame as a grid over the earth's surface; continents and parts of continents move under this grid and therefore the coordinates of any point will change over time, relative to the grid

THE EARTH IN MOTION

- The Mongolian territory belongs to the following two plates:
  - Western Mongolia: Eurasian plate, moving up to 3 – 4 mm / year towards the northeast
  - Central and Eastern Mongolia: Amur plate, moving approximately 2.5 mm / year towards the southeast
- Some urban cadastres claim centimetre accuracies…
- Modern geodetic GPS receivers achieve accuracies of up to 2 cm…
- Everything is relative – here, only local reference systems for small areas can provide easy solutions

THE EARTH IN MOTION





The Amur plate – a minor tectonic plate

EPOCH

- MONREF97 represents the physical local implementation of WGS-84/ITRF in Mongolia through 35 control points – but only at a certain point in time!
- Every year, the distance between MONREF97 and ITRF is growing
- To be exact, a term has been introduced to indicate the reference date of a datum: epoch
- MONREF97 = physical local implementation of ITRF at epoch 1997.8 (August)
- In 2014, a new campaign for updating was carried out: MONREF2014 = physical local implementation of ITRF2008 at epoch 2014.03.04
- Differences to MONREF97 up to > 4 cm
- Transformation algorithms (formulas) allow calculating coordinates in MONREF2014 from coordinates in MONREF97

SUMMARY

- Maps are an indispensable basis for managing many important tasks of the modern world (e.g. cadastre)
- The basis for mapping is a geometrical model of the earth's shape
- Models based on a definition of ellipsoid and datum have been established
- These models cannot fully describe the true shape of the earth; small inaccuracies need to be accepted
- Today, these models need to cover huge areas: entire countries, for some tasks the entire world (e.g. GPS)
- The standard in Mongolia is WGS-84
- If highest accuracy in the range of a few centimetres is required, geodetic reference systems need to be implemented (marked with benchmarks), and updated every couple of years (epoch)

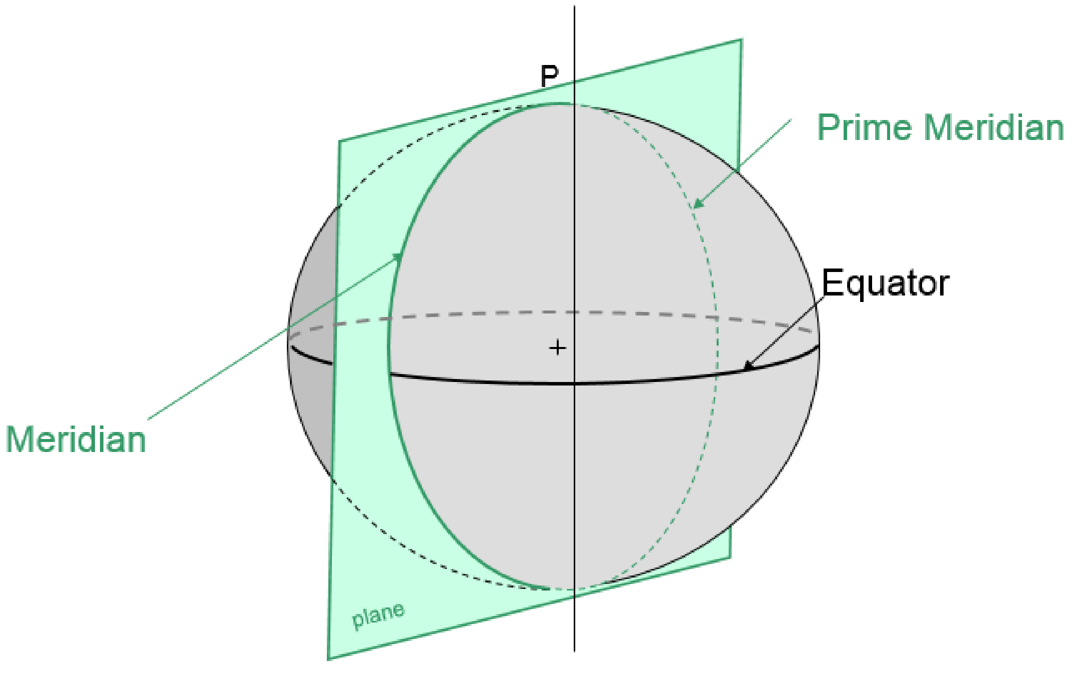
HORIZONTAL COORDINATE SYSTEMS

- Horizontal coordinate systems describe locations at the earth's surface using two coordinates (x/y)
- They are always based on a model of the earth's shape (ellipsoid and datum)
- Two approaches have been established:
  - Geographic coordinate systems
  - Projected coordinate systems

GEOGRAPHIC COORDINATE SYSTEMS

- Geographic coordinate systems are based on angles indicated in degrees

- Starting points: two planes, the prime meridian and the equator
- Prime meridian = 0° longitude
- Equator = 0° latitude



GEOGRAPHIC COORDINATE SYSTEMS

- 1 degree = 60 minutes = 3600 seconds
- Latitude expressed in linear units (all locations on the earth):
  - 1 degree latitude = ca. 100.6 km
  - 1 minute latitude = ca. 1850 m
  - 1 second latitude = ca. 30.7 m

  Exact values depend on datum and height!
- Longitude expressed in linear units:
  - Equator: 1 degree longitude = ca. 111.3 km
  - North and south pole: 1 degree longitude = 0 m
  - Ulaanbaatar:
    - 1 degree longitude = ca. 74 km
    - 1 second longitude = ca. 20.5 m
  - Dalanzadgad: 1 degree longitude = ca. 81 km

  Exact values depend on latitude, datum and height!

GEOGRAPHIC COORDINATE SYSTEMS

- Depending on the datum, the same place on earth can have different coordinates:
  - Pulkovo 42: Lat 49°00’00” Lon 105°00’00”
  - WGS-84: Lat 49°00’01.87 Lon 105°00’01.03”
- Due to their nature, geographic coordinates are sometimes difficult to handle:
  - How to calculate distances?
  - How to calculate areas?
  - How to store in computers? → decimal degrees
  - Suitable for spheroids, but actually not for flat (2D) maps

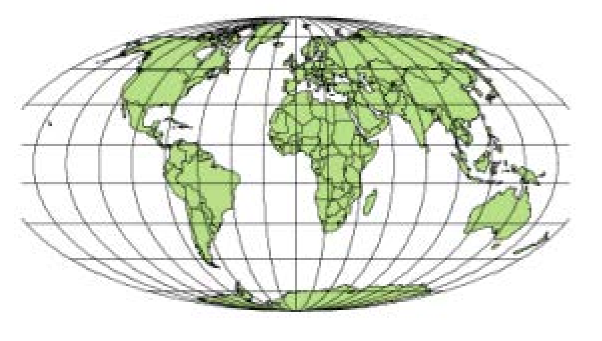
PROJECTED COORDINATE SYSTEMS

- Map projections are necessary for creating maps
- Map projections convert latitudes and longitudes on a spheroid to a plane (flat map)
- The convert the surface of a 3D object to a 2D object

PROJECTED COORDINATE SYSTEMS

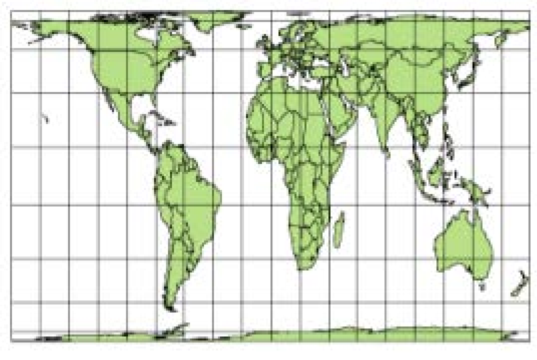
- All map projections distort the surface in some way
- Depending on the purpose of the map, some distortions are acceptable and others are not
- For this reason, many different map projections exist in order to preserve some properties at the expense of other properties:
  - Area (important e.g. for cadaster)
  - Shape (orientation, planning)
  - Direction (navigation)
  - Distance (navigation)
- Some projections preserve only one property, others preserve several properties with relatively small errors
- The bigger the area to be covered, the higher the error

PROJECTIONS

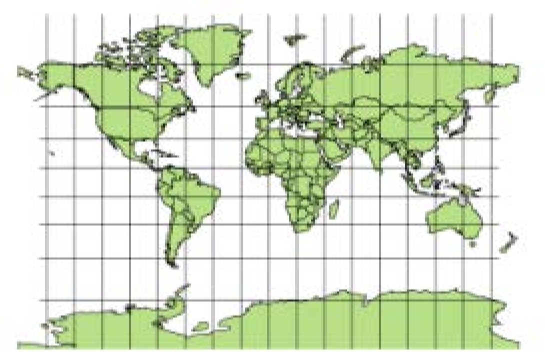


Mollweide-Projektion

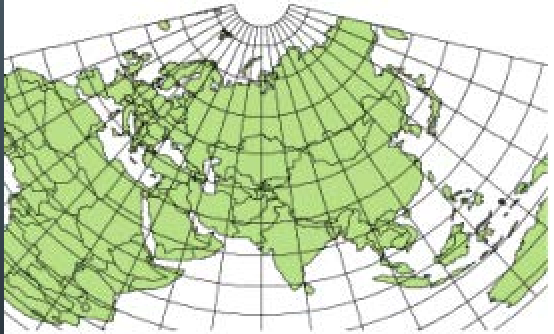
Mercator-Projektion



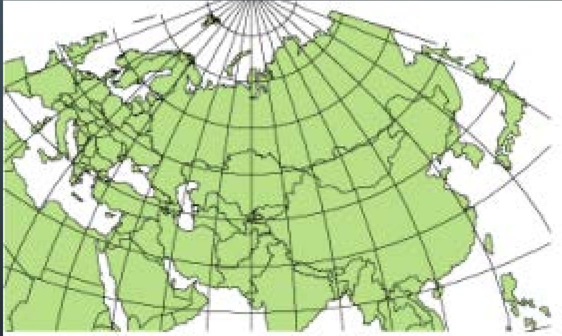
Peters-Projektion



Zylinderprojektion nach Miller



Flächentreue Kegelprojektion



Transverse Mercator-Projektion

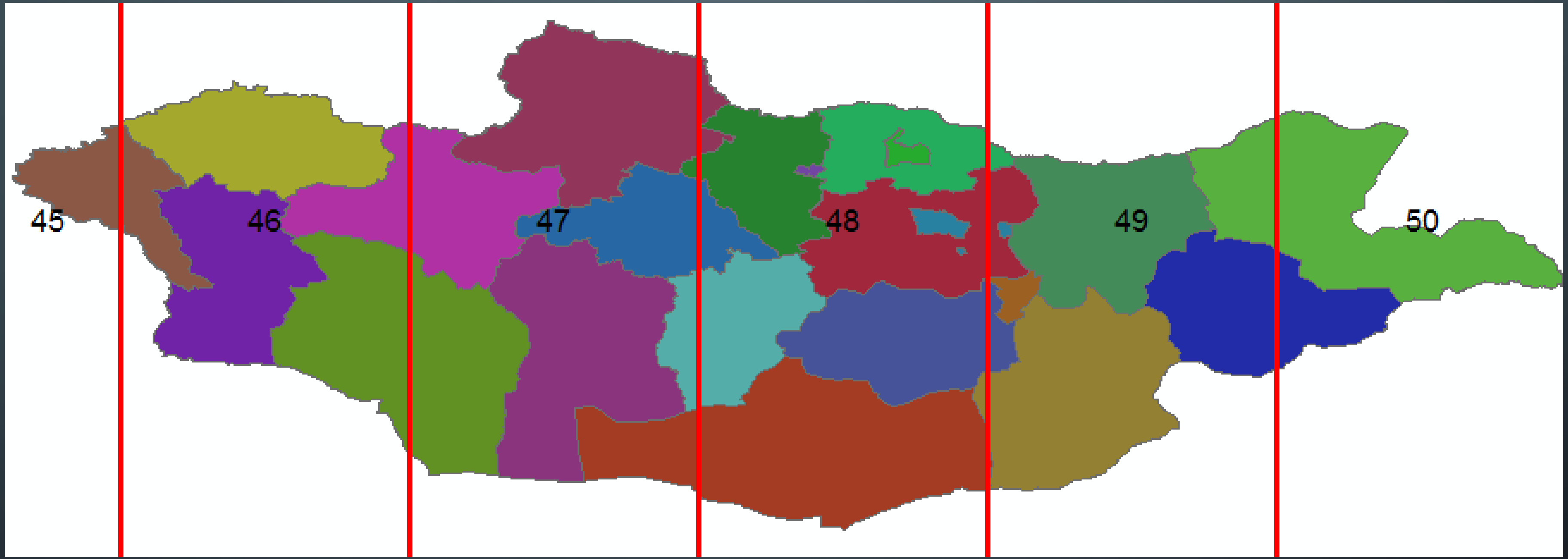
PROJECTIONS USED IN MONGOLIA

- Nationwide maps:
  - Lambert Conformal Conic Projection with standard parallels 41N/52N (also other parallels used)
  - Ellipsoid / datum: WGS-84
- Most common topographic, cadastre and other maps:
  - Till 2009:
    - Gauss-Krüger
    - Ellipsoid: Krasovski 1940
    - Datum: Pulkovo 1942
  - Since 2009:
    - UTM (Universal Transverse Mercator)
    - Ellipsoid / datum: WGS-84

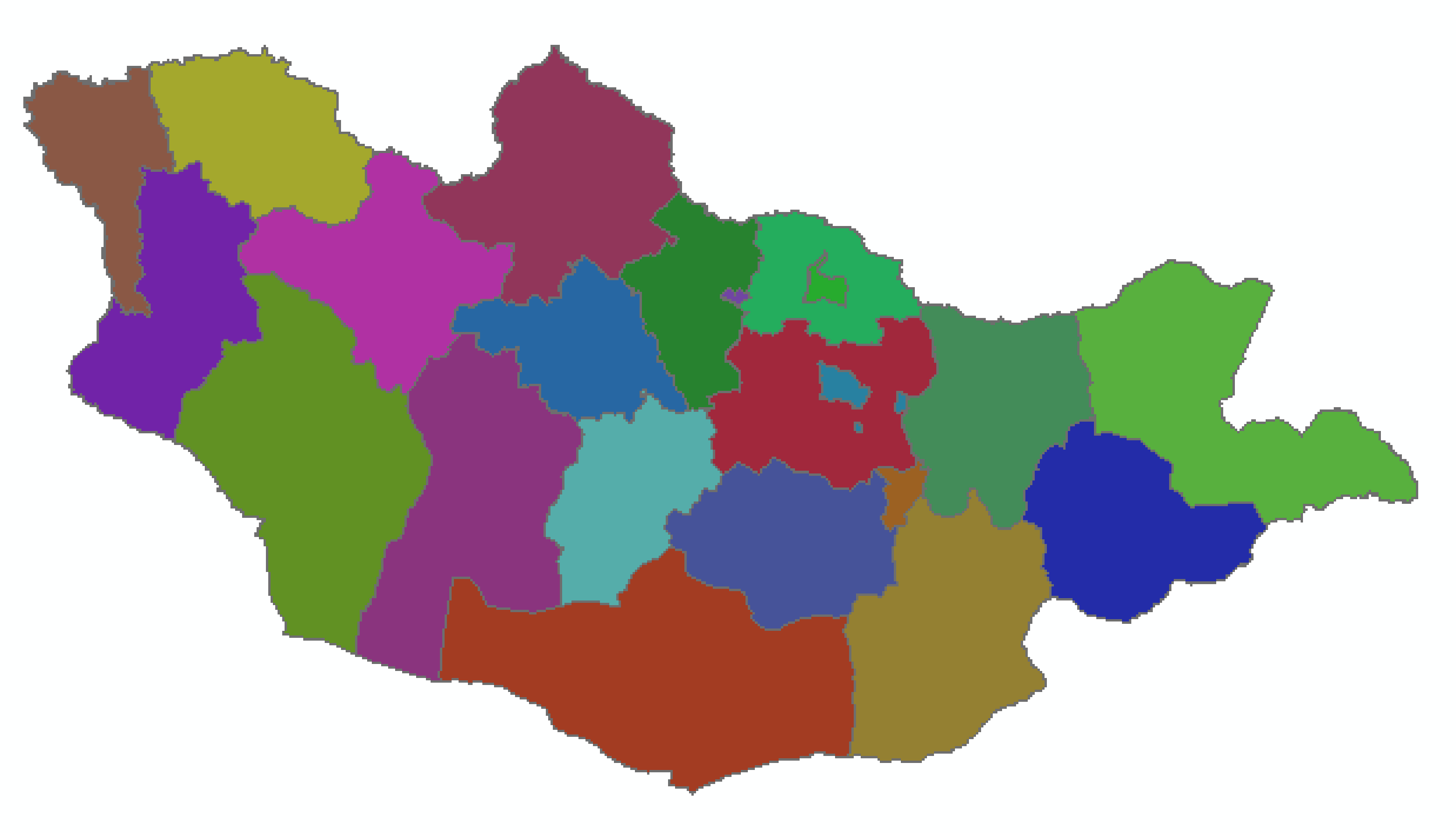
PROJECTIONS USED IN MONGOLIA: UTM

- UTM:
  - Conformal projection
  - Preserves directions / angles
  - Good approximation of shapes
  - Distortions in distances and areas
- To keep distortions acceptably low (< 0.1%) , UTM divides the world into zones of 6° longitude
- Note that:
  - UTM coordinates of different zones are not compatible
  - UTM coordinates make only sense if the zone is indicated
  - Maps can only be made within one zone

PROJECTIONS USED IN MONGOLIA: UTM ZONES



PROJECTIONS USED IN MONGOLIA: UTM ZONES



(Wrong) shape of Mongolia if making a map for the entire country using UTM projection

TRANSFORMATIONS AND (RE)PROJECTION

- Transformation: conversion of coordinates and maps between different datums
- Different algorithms can be used:
  - Parametric methods
  - Grid-based methods
- Would be relatively easy if implemented datums (geodetic reference systems) followed exactly their geometric / mathematical definition, but in many cases they do NOT
- Mongolia: transformation between Pulkovo 1942 and WGS-84:
  - Parametric method: high error in some areas
  - Grid-based method: MODCON (software, ArcMap plug-in)
    - Elaborated in 2009 (World Bank / CMCS)
    - Used for conversion of all mining cadastre and protected area data
    - Assumed error ca. 1 m on average

TRANSFORMATIONS AND (RE-)PROJECTION

- Projection: conversion of geographic coordinates to a projected coordinate system (without change of datum)
- Re-projection: conversion of coordinates between two projected coordinate systems (without change of datum), e.g. Gauss-Krüger → UTM
- Both procedures are based on mathematic algorithms and do not introduce any significant error

SUMMARY

- Geographic coordinate systems assign unambiguous coordinates to locations on the surface of the earth
- They are not useful for maps and measurements (length, areas)
- If using geographic coordinate systems, the following information MUST be provided, otherwise the coordinates are useless:
  - Ellipsoid
  - Datum

SUMMARY

- Projected coordinate systems allow:
  - Creating maps
  - Measuring distances, areas, directions
- They cannot preserve all characteristics of the earth's surface in the same way
- Some projections are only valid for limited areas (zones)
- If using projected coordinate systems, the following information MUST be provided, otherwise the coordinates / maps are useless:
  - Ellipsoid
  - Datum
  - Projection name
  - Zone

SUMMARY

- Since 2009, WGS-84 is the official ellipsoid and datum of Mongolia
- All coordinate data and maps (e.g. cadastre data, mining plans) MUST use this reference system
- Coordinates can be indicated either in geographic or in UTM coordinates
- Maps are required to use the projection UTM
- In 2009, all mining companies were informed accordingly and received license perimeter data referenced to the new datum, and updated license area sizes (!)

IMPLICATIONS FOR GEOLOGICAL MAPS

- ArcGIS can transform all kinds of spatial data from one datum to another (on-the-fly, and by saving to a new file)
- Basic requirement: all datasets MUST have correct coordinate system information assigned
- Datum transformations always result in loss of accuracy; choose the most suitable transformation method to keep the loss as low as possible! Pulkovo-42 → WGS-84: use MODCON!
- ArcGIS can project and re-project data to and between different projections (e.g. UTM, Gauß-Krüger; on-the-fly, and by saving to a new file); if no datum transformation is involved, this process maintains the original accuracy (no loss)!
- UTM is NOT a suitable projection for maps covering the entire country! Several more suitable projects are available, such as Lambert Conformal Conic

```
Projection: Lambert_Conformal_Conic
False_Easting: 0,0
False_Northing: 0,0
Central_Meridian: 103,0
Standard_Parallel_1: 43,0
Standard_Parallel_2: 51,0
Scale_Factor: 1,0
Latitude_Of_Origin: 30,0
Linear Unit: Meter (1,0)
```

IMPLICATIONS FOR THE MINING CADASTRE

- At least two types of cadastre are to be distinguished:
  - Land / urban cadastre
  - Mining cadastre
- Cadastre coordinates can never be "100% exact"! Questions:
  - What would "100%" mean? 10 m? 1 m? 1 cm?
  - How much accuracy makes sense? Compare urban, rural and exploration applications…
- To mitigate the implications of what was mentioned on the previous slides, and to keep surveying efforts reasonable, many countries have set accuracy levels for cadastre applications:
  - Either in distances (metres)
  - Or through defining a reference scale:
    - Mining cadastres: often between 1:20 000 – 1:100 000 depending on the official base map quality
    - Then, the accuracy for mapping at this scale applies

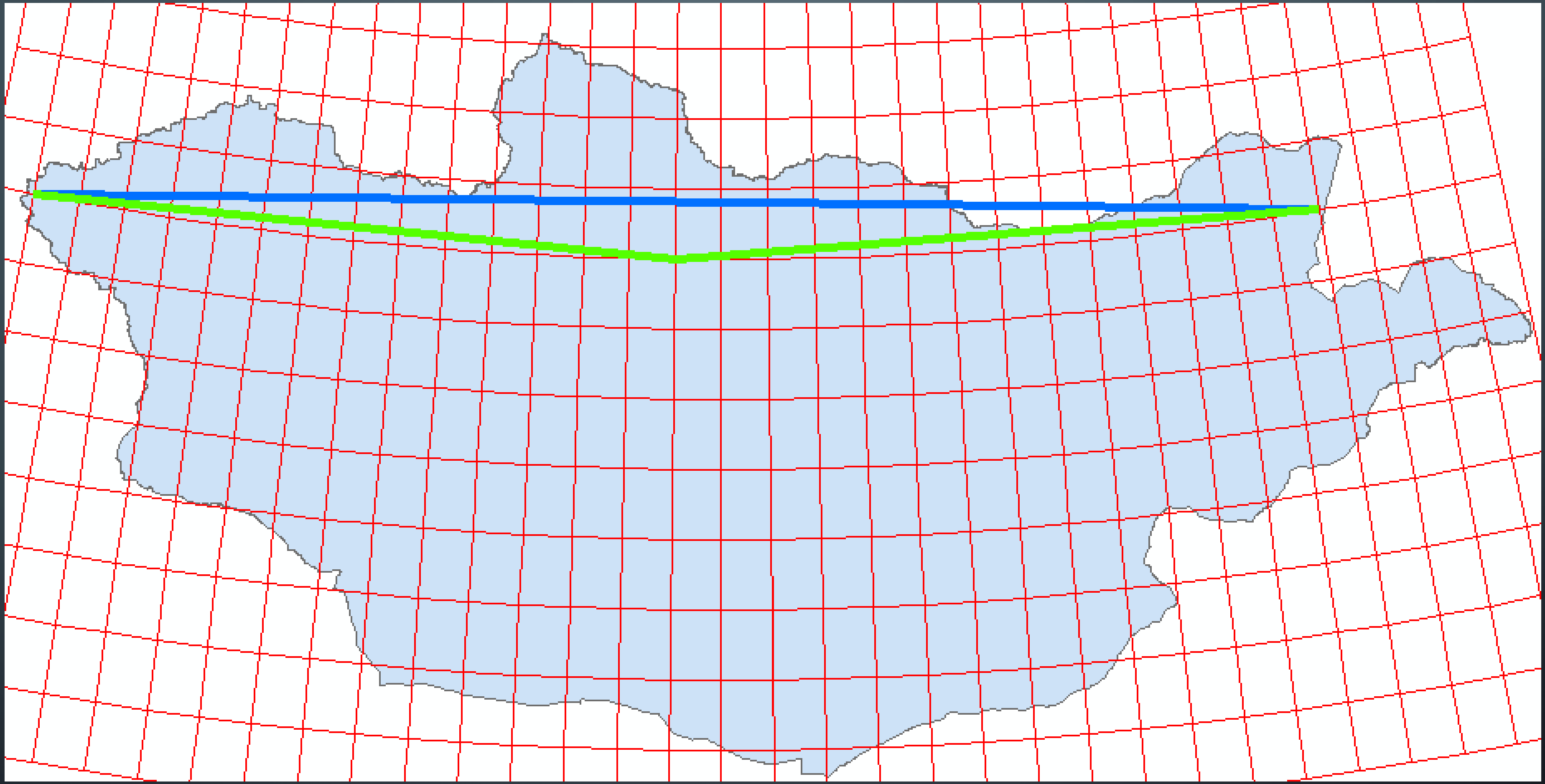
IMPLICATIONS FOR THE MINING CADASTRE

- Mongolia's Minerals Law does not explicitly mention an accuracy requirements, or a reference scale, but it can be assumed the reference is the only topographic map series available for the entire country: 1:100 000 scale
- According to Mongolian standards, the horizontal accuracy of maps at scale 1:100 000 is 50 metres!
- Questions:
  - Is an overlap of two license areas of 5 metres really an overlap?
  - Is it a problem if a license area overlaps with a protected forest by 1 metre? Where exactly does a forest start, where the tree trunk comes out of the soil, where the underground roots end, or what is covered by the treetop?
  - Does it make any sense to have "corner coordinates" of protected forests every 50 cm?

IMPLICATIONS FOR THE MINING CADASTRE

- According to the Minerals Law, license area boundaries are “straight lines following the latitude / longitude grid”
- Questions:
  - Can such a line between two points be “straight” in the reality?
  - Can two licenses, one granted when Pulkovo 42 was the official coordinate system, one granted when WGS-84 was the official coordinate system, really share a common boundary?
- Let’s have a look at two “straight” lines defined by geographic coordinates:
  - Line 1: 49° N / 88° E – 49° N / 116° E
  - Line 2: 49° N / 88° E – 49° N / 102° E – 49° N / 116° E

IMPLICATIONS FOR THE MINING CADASTRE



Mongolia, WGS-84 latitude / longitude grid; blue line (1) = “straight line” defined by 2 coordinates, green line (2) = “straight line” defined by 3 coordinates; in reality, non of these lines is really straight! And: only a curve would be parallel to the latitude line!

WHAT ABOUT ELEVATIONS?

- Thus far, we have only been talking about horizontal reference systems
- How to indicate elevations of:
  - The terrain (earth's surface)
  - Objects located on the surface of the earth (ground elevation + object height)
  - Objects located above (aircrafts) or below (underground mining, tunnels, sewage water systems)?

  → Vertical reference systems are required

MEAN SEA LEVEL

- For most of the time, elevations were related to a “mean sea level”, measured in a city located at the sea
- The sea level was measured over several years (impact of tides, winds), then an average level was calculated and marked with a monument
- The oldest of such reference points: Amsterdam Ordnance Datum (Normaal Amsterdams Peil), erected in 1684 and used in Holland and other countries such as Germany

MEAN SEA LEVEL

- Later on, similar reference points were established in other cities all over the world, for instance in 1833 in Kronstadt, Russia, indicating the Baltic Sea Level (used in many countries such as Mongolia)
- What scientists did not know at that time: the sea level is changing constantly due to several factors such as:
  - Climate (amount of water in the oceans versus fresh water in rivers, glaciers, air)
  - Sea currents
  - Predominant wind directions
  - Continental ground heaving or depression
  - Changes of the shape of the coast
  - …
- Today, the Normaal Amsterdams Peil is approximately 40 cm over the current mean sea level of the North Sea…

EXTRAPOLATION OF THE MEAN SEA LEVEL

- How to measure the *elevation above the mean sea level* in cities such as Amsterdam is clear, but what about Mongolia? Where is the *mean sea level* here where we don't have any sea?
- Geodesists once believed that the sea was in balance with the earth's assumed regular gravity forming a perfectly regular geometric figure
- Based on this assumption, methods were elaborated to define the *elevation above mean sea level* for places without direct connection to a sea

EXTRAPOLATION OF THE MEAN SEA LEVEL

- Using these methods, further reference points were set up in cities for from the sea
- Elevations referenced to such reference points are called *orthometric heights*
- Unfortunately, accuracy is difficult to achieve:
  - Highest (first order) accuracy standard used in Germany:

    1 mm per 1 km
  - Distance Amsterdam – München 670 km → 67 cm error would acceptable
  - Distance Kronstadt – Ulaanbaatar 4885 km → 4.88 m error would be acceptable even applying highest German standards!!
- Any alternative to these methods?
  - Gravity surveys
  - Astronomy: determination of vertical deflections with a zenith camera
- Why not using *ellipsoidal elevations*?

ELLIPSOIDAL ELEVATIONS

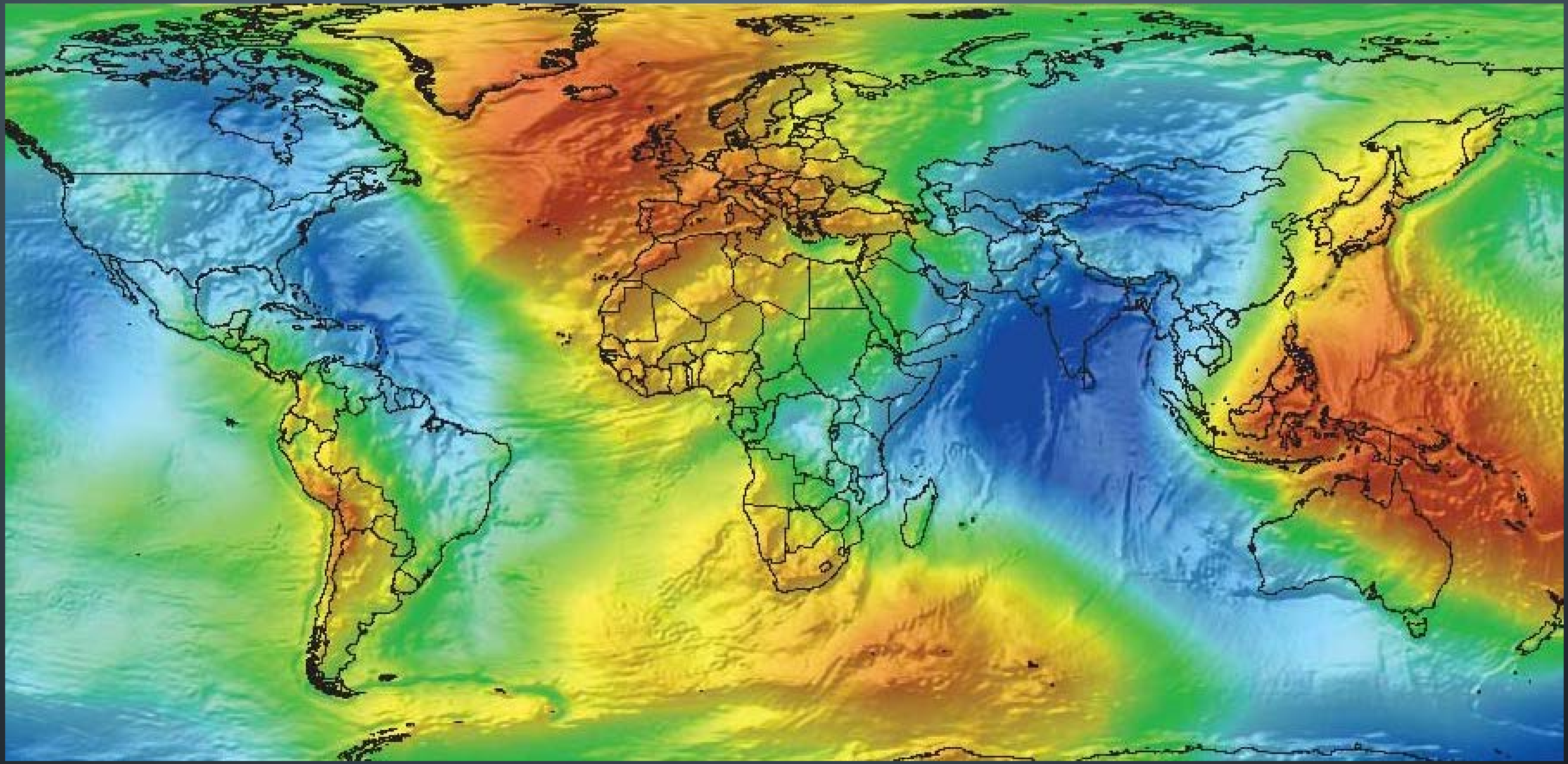
- Ellipsoids are objects which can be perfectly described with mathematical formulas
- An ellipsoid of rotation (datum) is an approximation to the earth's surface at sea level, thus why not using this as elevation reference?
- Modern satellite measurements can:
  - Produce good datums (e.g. WGS-84)
  - Calculate 3D coordinates references to these datums at any place of the earth
- Problem solved?

ELLIPSOIDAL ELEVATIONS

- Satellite measurements showed huge irregular differences of up to dozens of meters between mean sea levels and ellipsoidal elevations ☹
- In some areas, water actually flows against the ellipsoidal downhill-grade!
- The Topex/Poseidon satellite mission (1992) measured sea levels around the globe and proved that the observed differences between actual sea levels and ellipsoidal elevations are:
  - Not a calculation or measurement error
  - Irregular

  …and showed that the assumption of geodesists *that the sea is in balance with the earth's gravity forming a perfectly regular geometric* figure was <u>wrong</u>!!

ELLIPSOIDAL ELEVATIONS



Differences between WGS-84 elevations and “true” sea levels; red = true level higher than WGS-84; estimations over continents

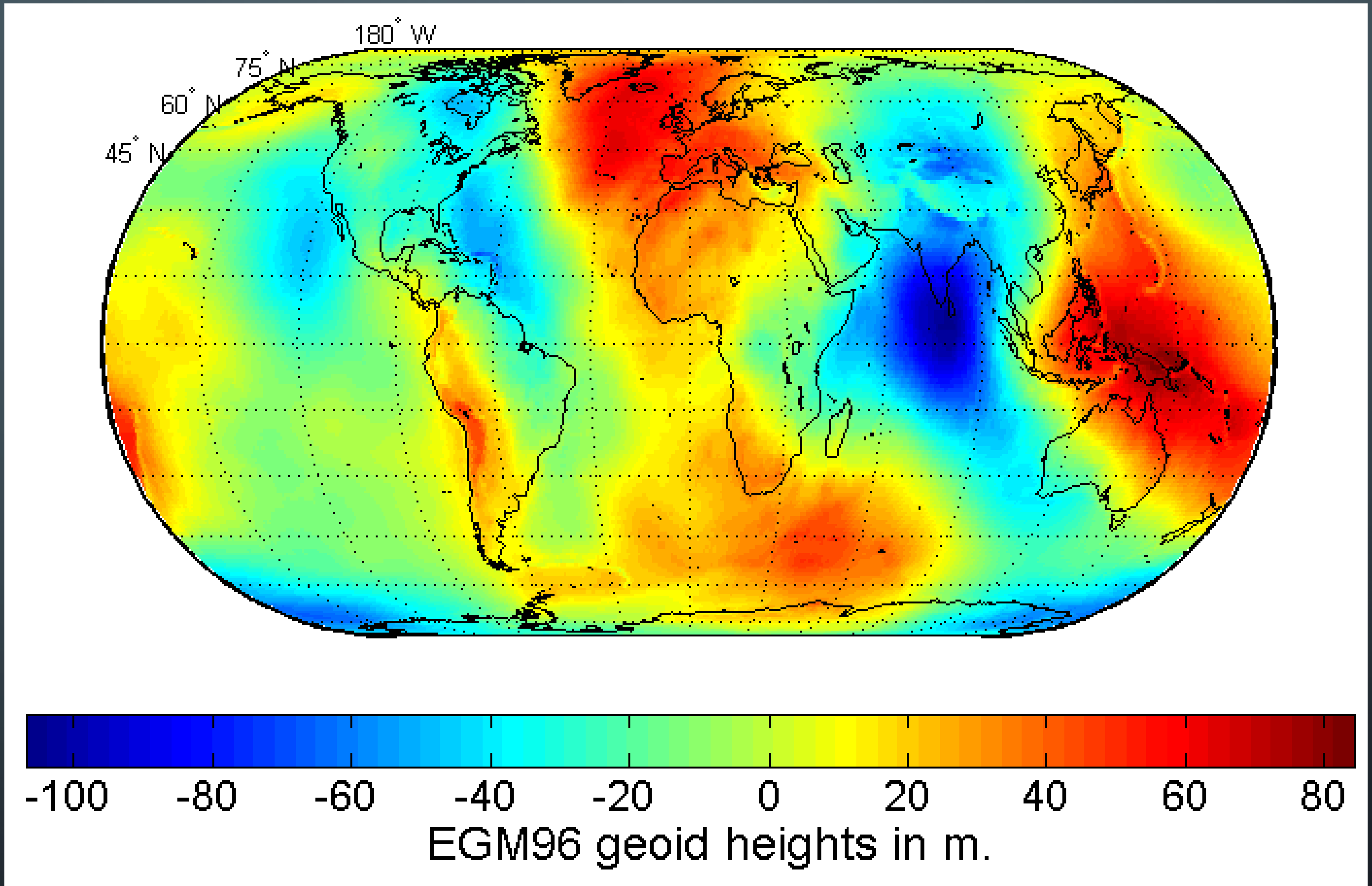
GEOIDS

- Observed maximum differences:
  - Southeast of India: WGS-84 105 m higher than sea level
  - Eastern Indonesia: WGS-84 87 m lower than sea level
- Reason for the observed differences: gravity anomalies and gravity disturbances, e.g. under subduction zones, and caused by different magma densities (greater density → higher → greater gravity → stronger pull → accumulation of water masses)
- It is not sure if these anomalies tend to move, but if they do, they probably (and hopefully) move very slowly
- **Solution:**
  - **In a certain way, come back to the orthometric elevations concept**
  - **Measure gravity anomalies and disturbances**
  - **Create a *geoid* model as global vertical reference system**
- Geoid = surface of constant gravitational potential

THE EGM-96 GEOID

- EGM-96: Earth Gravitational Model 1996
- Developed by US National Imagery and Mapping Agency, NASA and Ohio State University
- Main basis: gravity survey data (space-, ground- and airborne), satellite measurements (oceans)
- EGM-96 is used as horizontal reference system for the WGS-84 datum
- EGM-96 is assumed to have an accuracy of better than 1 m (except some few areas where gravity data were missing)
- EGM-96 will not be the final geoid (already: EGM 2008, 2014):
  - More and denser gravity survey data
  - Better theoretical understanding
  - Better calculation methods

THE EGM-96 GEOID



EGM-96 AND THE (MONGOLIAN) BALTIC SEA LEVEL

- EGM-96: a global geoid / vertical reference system
- **(Mongolian) Baltic Sea Level:** a regional vertical reference system
- Difference:
  - Very few meters, varying all over Mongolia
  - Ulaanbaatar: EGM-96 elevations are around 1 m higher
- GPS:
  - EGM-96 reference system is incorporated
  - Mongolian Baltic Sea Levels need to be calculated using the local vertical geodetic reference grid (benchmarks)
- Which one is better for high-precision infrastructure works? None of them is sufficient! → Ulaanbaatar Municipality is working on a local geoid…