Preface third edition

Geographical Resources Analysis Support System (GRASS) is one of the largest Free Software Geographical Information System (GIS) projects released under the GNU General Public License (GPL). It combines powerful raster, vector, and geospatial processing engines into a single integrated software suite and includes tools for spatial analysis, modeling, image processing and sophisticated visualization.

With this third edition of *Open Source GIS: A GRASS GIS Approach*, we enter the new era of GRASS 6, the first release that includes substantial new code developed by the International GRASS Development Team. It comes at a time when dramatic growth in acceptance of the Open Source concept fuels further development of Free and Open Source Software for Geoinformatics (FOSS4G) and brings interoperability to a new level of efficiency. The major FOSS4G projects, including GRASS, have become part of the OSGeo foundation – an organization established in 2006 to "support and promote the collaborative development of open geospatial technologies and data." Following the spirit of the foundation, GRASS is tightly integrated with the latest GDAL/OGR and PROJ libraries supporting range of raster and vector formats, as well as projections. GRASS toolkits for Quantum GIS (QGIS) and R Project for Statistical Computing have been developed thanks to strong links with these projects.

The third edition of *Open Source GIS: A GRASS GIS Approach* reflects these new developments. The first chapter includes information about the OSGeo foundation. Chapter three that introduces GRASS and the new sample data set, has added information about the new graphical user interfaces that can be used with GRASS 6. The properties of GRASS raster and vector data are described in chapter four, which also includes extensive material on importing data in various formats, and an introduction to new geocoding tool. The raster chapter has been enhanced with new examples, more comprehensive topographic analysis and modeling, and introduction to voxel data processing. The chapter on vector data has been completely rewritten to reflect introduction of a new vector data format and attribute support through database management system (DBMS) in GRASS 6. This chapter now includes new sections on attribute database management and SQL support, vector networks analysis, linear reference systems, and lidar data applications. The site data chapter of earlier book editions was integrated within the chapter six as vector point data processing section. The visualization chapter reflects the changes in 2D display, nviz, and use of Paraview. Image processing was reduced and updated, orthophoto chapter was eliminated to make space for more new material. Application chapter was merged with raster analysis. Equations and SQLite-ODBC connection guide were added into Appendix. All chapters were enhanced with numerous practical examples using the first release of a free, comprehensive, state-of-the-art geospatial data set. The examples are based on the GRASS 6.3 version from July 2007.

Finally, we briefly recall history of GRASS and this book: GRASS was developed in 1982-1995 by the U.S. Army Corps of Engineers Construction Engineering Research Laboratory (CERL) in Champaign, Illinois to support land management at military installations. After CERL withdrew from further GRASS development in 1995, the GRASS 4.2.1 release, published in 1998, was coordinated by this book's author at the Institute of Physical Geography and Landscape Ecology, University of Hannover. The development of the GRASS 5.0 release started in 1999 when GRASS was released under GPL. Since 2001, the "GRASS Development Team" has its headquarters at FBKITC-irst (Centro per la Ricerca Scientifica e Tecnologica), Trento, Italy. GRASS 5.0.0 was officially released in 2002, accompanied by the first FOSS4G – GRASS users conference held in September 2002 in Trento, Italy, and by the publication of the first edition of this book.

The book has its own history. It started as "GRASS Recipes" written in 1995 for students at the Institute of Landscape Architecture, University of Hannover. In 1996, the first continuous German text was written and later published in "Geosynthesis" series at the Geographical Institute, University of Hannover. The first english edition of the book, published in June 2002, was the result of collaborative work of a number of translators and a new coauthor. It was written for the GRASS 5.0pre3 release. The second edition, published in 2004, was based on the GRASS 5.3 release and included updates reflecting the system enhancements and the feedback from our readers. This third edition is based on GRASS 6 and represents a fundamental update and enhancement of the material.

The GRASS project's Web site, providing access to the GRASS software and documentation, can be reached at "GRASS Headquarters" at `http://grass.itc.it` and a number of mirror sites. The material related to this book can be accessed at `http://grassbook.org`.

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2

GIS concepts

To use GIS effectively, it is important to understand the basic GIS terminology and functionality. While each GIS software has slightly different naming conventions, there are certain principles common to all systems. At first, we briefly describe the GIS basics in general (for in depth information read Longley et al., 2005, Clarke, 2002, or Burrough and McDonnell, 1998) and then we explain the principles of map projections and coordinate systems that are used to georeference the data.

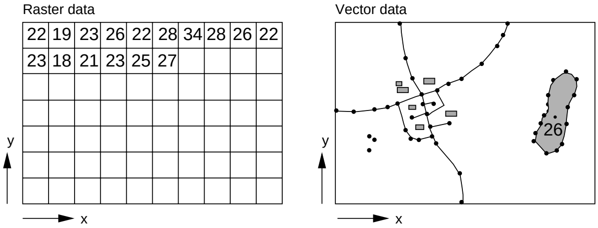
2.1 General GIS principles

Data in a GIS database provide a simplified, digital representation of Earth features for a given region. Georeferenced data can be organized within GIS using different criteria, for example, as thematic layers or spatial objects. Each thematic layer can be stored using an appropriate data model depending on the source of data and their potential use.

2.1.1 Geospatial data models

Georeferenced data include a *spatial* (geometrical or graphical) component describing the location or spatial distribution of geographic phenomenon and an *attribute* component used to describe its properties. The spatial component can be represented using one of the two basic approaches (Figure 2.1):

- *field* representation, where each regularly distributed point or an area element (pixel) in the space has an assigned value (a number or no-data), leading to the *raster data model*;
- *geometrical objects* representation, where geographic features are defined as lines, points, and areas given by their coordinates, leading to the *vector data model*.



Attribute data

cat	soilname	area
1	Ro	243017.6
2	Wo	13426100.1
3	Au	433044.4
4	GrC	466433.7
5	PkC	119344.9

Fig. 2.1. Data models in GIS – raster and vector data with attribute table: *Raster data:* rows and columns of values representing spatial phenomenon; *Vector data:* representation by points, lines and areas; *Attributes:* descriptive data stored in a database table

Depending on scale, representation of a geographic feature can change; for example, a river can be handled as a line at small scale or as a continuous 3D field (body of water) at large scale. Similarly, a city can be represented as a point or as an area. Note that we use the terms small and large scale in the cartographic sense, for example, 1:1million is small scale, 1:1000 is large scale.

To effectively use GIS, it is useful to understand the basic properties and applications of each data model (in older GIS literature, the raster and vector data models have been often referred to as raster and vector data formats).

Raster data model Raster is a regular matrix of values (Figure 2.1). If the values are assigned to *grid points*, the raster usually represents a continuous field (elevation, temperature, chemical concentration) and is sometimes called *lattice*. If the values are assigned to *grid cells* (area units, pixels), it represents an image (satellite image, scanned map, converted vector map). If the cell values represent category numbers, one or more attributes can be assigned to that cell using a database. For example, a soil type with category number 3 can have attributes describing its texture, acidity, color and other properties. The grid cells are organized and accessed by *rows* and *columns*. The area represented by a square grid cell is computed from the length of its side, called *resolution*. Resolution controls the level of spatial detail captured by the raster data. Most data are represented by a 2D raster, with the grid cell (unit area) called a *pixel*; volume data can be stored as a 3D raster with a unit volume called a *voxel* (volume pixel). General d-dimensional raster formats are used for spatio-temporal or multispectral data (e.g. HDF format[1]).

The raster data model is often used for physical and biological subsystems of the geosphere such as elevation, temperature, water flow, or vegetation. However, it can also be used for data usually represented by lines and polygons such as roads or soil properties, especially for scanned maps. The raster data model was designed with a focus on analysis, modeling and image processing.

[1] HDF format and tools, `http://www.hdfgroup.org/`

Its main advantage is its simplicity, both in terms of data management as well as the algorithms for analysis and modeling, including map algebra. This data model is not particularly efficient for networks and other types of data heavily dependent on lines, such as property boundaries. GRASS has extensive support for the raster data model.

Vector data model Vector data model is used to represent areas, lines and points (Figure 2.1). We describe the vector data model using GRASS terminology; in other systems, the definitions may be slightly different.

The vector data model is based on *arc-node* representation, consisting of non-intersecting lines called *arcs*. An arc is stored as a series of points given by (x, y) or (x, y, z) coordinate pairs or triplets (with height). The two endpoints of an arc are called *nodes*. Points along a line are called *vertices*. Two consecutive (x, y) or (x, y, z) pairs define an *arc segment*. The arcs form higher level map features: *lines* (e.g., roads or streams) or *areas* (e.g., farms or forest stands). Arcs that outline areas (polygons) are called *area edges* or *boundaries*. A complete area description includes a *centroid*. In GRASS, 3D polygons are called *faces* (they do not need a centroid but can be visualized). A 3D volume is a closed set of *faces* including a 3D centroid (*kernel*). Not all GIS software packages support 3D vector data types. Linear features or polygon boundaries are drawn by straight lines connecting the points defining the *arc segments*. To reduce the number of points needed to store complex curves, some GIS include mathematically defined *curve sections* or *splines* that are used to compute the points with the required density at the time of drawing.

In addition to the coordinate information, the vector data model often includes information about the data *topology* which describes the relative position of objects to each other (see Section 6.3.1 for more details on vector data topology).

Each map feature is assigned a category number which is used to link the geometric data with descriptive, attribute data (such as category labels or multiple attributes stored in a database). For example, in a vector map "roads", a line can be assigned category number 2 with a text attribute "gravel road" and a numerical attribute representing its width in map units.

Point features (e.g., a city or a bridge) or point samples of continuous fields (e.g., elevation, precipitation), are represented as independent points given by their coordinates. A value or a set of attributes (numerical or text) is assigned to each point.

Vector data are most efficient for discrete features which can be described by lines with simple geometry, such as roads, utility networks, property boundaries, building footprints, etc. Continuous spatial data can be represented by vector data model using isolines, point clouds or various types of irregular meshes; however, such representations usually lead to more complex algorithms for analysis and modeling than the raster data model. GRASS 6 provides support for both the 2D and 3D multi-attribute vector model.

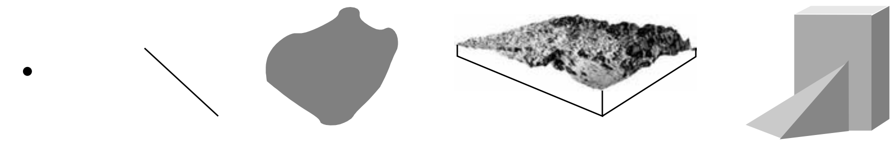


Fig. 2.2. Data dimensions in a Geographical Information System (after Rase, 1998:19)

Attributes – GIS and databases Attributes are descriptive data providing information associated with the geometrical data. Attributes are usually managed in external or internal GIS database management systems (DBMS). The databases use the corresponding coordinates or identification numbers to link the attributes to the geometrical data. Some systems, such as PostGIS[2] or, with some limitations, MySQL also allow the user to store geometrical data into the database.

For raster data, GRASS supports only a single attribute for each cell category. For vector data, GRASS offers a generic SQL-DBMS abstraction layer with two choices for internal databases (limited DBF file driver, and SQLite driver) and several full featured interfaces to external databases (PostgreSQL, MySQL, and ODBC interface to various DBMS). Multiple attributes can be stored and managed for each vector object. One or several attribute tables can be linked to a vector map.

Data model transformations The same phenomenon or feature can be represented by different data models. GIS usually includes tools for transformation between the vector and raster data model. For example, elevation can be measured as vector point data, then interpolated into a raster map which is then used to derive contour lines as vector data. Note that transformations between different data models are usually not lossless (there can be a loss or distortion of information or spatial displacement due to the transformation).

Dimensions of geospatial data In general, Earth and its features are located and evolve in 3D space and time. However, for most applications a projection of geospatial data to a flat plane is sufficient; therefore two-dimensional representation of geographical features (with data georeferenced by their horizontal coordinates) is the most common. Elevation as a third dimension is usually stored as a separate raster map representing a surface within three-dimensional space (often referred to, not quite correctly, as a 2.5-dimensional representation, Figure 2.2). Elevation can be also added as a z-coordinate or as an attribute to vector data. If there is more than a single

[2] PostGIS DBMS, `http://postgis.refractions.net`

z-value associated with a given horizontal location, the data represent a volume and are three-dimensional (e.g., chemical concentrations in groundwater, or air temperature). Three-dimensional data can change in time, adding the fourth dimension. GIS provides the most comprehensive support for 2D data. GRASS 6 includes a 3D raster model for volume data and a 3D vector model for multi-attribute vector data (see Brandon et al., 1999; Neteler, 2001; Blazek et al., 2002); however, only a limited number of modules is available for true volume data processing and analysis.

2.1.2 Organization of GIS data and system functionality

GIS can be implemented as a comprehensive, multipurpose system (e.g. GRASS, ArcGIS), as a specialized, application oriented tool (e.g. GeoServer, MapQuest), or as a subsystem of a larger software package supporting handling of geospatial data needed in its applications (e.g., hydrologic modeling system, geostatistical analysis software, or a real estate services Web site). The multipurpose systems are often built from smaller components or modules which can be used independently in application oriented systems.

The multipurpose GIS usually stores the georeferenced data as thematic *maps*. Each geographic feature or theme, such as streams, roads, vegetation, or cities is stored in a separate map using the vector or raster data model. The maps can then be combined to create different types of new maps as well as perform analysis of spatial relations. GRASS and most of the proprietary GIS products are based on this data organization.

A large volume of geospatial data is nowadays distributed through *Internet based GIS* and *Web Services*. The data sets are stored on central server(s) and users access the data as well as the display and analysis tools through the Internet. Examples are the browser based interactive maps and virtual globes (Google Earth, NASA WorldWind etc.), National Map of the U.S.[3], UMN/MapServer Gallery[4]. Almost every multipurpose GIS software includes tools supporting development of Web-based applications. GRASS can be used with UMN/MapServer, an Open Source project for developing Web-based GIS applications which supports a variety of spatial requests like making maps, scale-bars, and point, area and feature queries (see Chapter 10). Creation of interactive maps, including MapServer, OpenEV, GDAL/OGR, and PostGIS on the Internet, is described in Mitchell (2005) and Erle et al. (2005). The availability of public programming interfaces by many Web mapping providers inspires implementation of "mashups" that aggregate different (Web based) services into new value-added applications.

Other projects such as JGrass/uDig[5] are using JAVA to implement a client/server model. A new approach is the implementation of OGC Web Processing Service (WPS) in Python, the PyWPS software (see Section 9.3.2).

[3] National Map of the U.S., `http://nationalmap.gov`
[4] UMN/MapServer Gallery, `http://mapserver.gis.umn.edu`
[5] JGrass/uDig (JAVA GRASS Client-Server) Web site, `http://www.jgrass.org`

Internet GIS can be enhanced by interactive 3D viewing capabilities using GeoVRML[6] as well as by multimedia features adding photographs, video, animations or sound to the georeferenced data.

While creating digital and hardcopy maps has been the core GIS function over the past decade, the emphasis is shifting towards Web Services, spatial analysis and modeling. GIS functionality is rapidly evolving and currently covers a wide range of areas, for example:

- integration of geospatial data from various sources: projections and coordinate transformations, format conversions, spatial interpolation, transformations between data models;
- visualization and communication of digital georeferenced data in form of digital and paper maps, animations, virtual reality (computer cartography);
- spatial analysis: spatial query, spatial overlay (combination of spatial data to find locations with given properties), neighborhood operations, geostatistics and spatial statistics;
- image processing: satellite and airborne image processing, remote sensing applications;
- network analysis and optimization;
- simulation of spatial processes: socioeconomic such as transportation, urban growth, population migration as well as physical and biological, such as water and pollutant flow, ecosystem evolution, etc.

The most rapid and innovative development in geospatial technologies is currently linked to integration of geospatial information within various aspects of Web capabilities and services such as:

- Geospatial Web and Semantic Web (content can be read and used by software agents);
- Service Oriented Architecture (SOA) and Web Services – for example, PyWPS, GeoServer, UMN/MapServer, deegree;
- Geotagging and GeoRSS: addition of geographical identification to various media to support mapping and location-based search;
- Sensor Web: processing and serving real time georeferenced data acquired by multiple sensors;
- Map tiling for projection on virtual globes – or example, OSGeo tiling project;
- building communities that share geospatial data and develop geospatial applications and mashups; using geospatial concepts within Web 2.0.

OSGeo foundation plays a major role in the development of these new technologies.

GIS functionality is used to solve spatial problems in almost every area of our lives. Here are a few examples. In the area of socioeconomic applications,

[6] GeoVRML Web site, `http://www.geovrml.org`

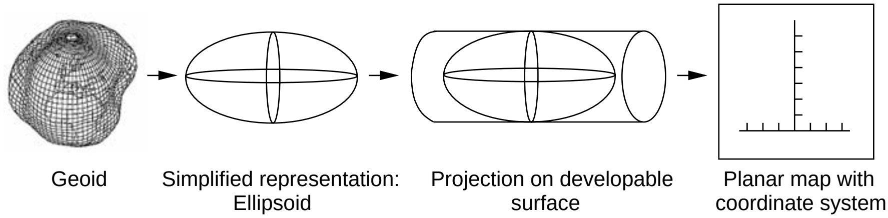


Fig. 2.3. Earth's surface representation in map projections and coordinate systems

GIS can be used to find directions, locate a hospital within a given distance from a school, find optimal locations for a new manufacturing facility, design voter districts with given composition and number of voters, identify crime hot spots in a city, select optimal evacuation routes, manage urban growth. GIS plays an important role in conservation of natural resources, agriculture, and management of natural disasters, such as identification and prevention of soil erosion risk, forest resource management, ecosystem analysis and modeling, planning of conservation measures, flood prediction and management, pollutant modeling, and more.

2.2 Map projections and coordinate systems

The basic property of GIS, as opposed to other types of information systems, is that the stored data are georeferenced. That means that the data have defined location on Earth using coordinates within a georeferenced coordinate system. The fact that Earth is an irregular, approximately spherical object makes the definition of an appropriate coordinate system rather complex. The coordinate system either has to be defined on a sphere or ellipsoid, leading to a system of geographic coordinates or the sphere has to be projected on a surface that can be developed into a plane where we can define the cartesian system of coordinates (*easting, northing and elevation*; see Sections 2.2.2).

2.2.1 Map projection principles

When working with GRASS, the projection and coordinate system must be defined whenever a new project (LOCATION in GRASS terminology) is created. The map projection definition is stored in an internal file within the given LOCATION. It is used whenever the data need to be projected into a different projection or when calculations requiring information about the Earth's curvature are performed. Different parameters are needed to define different projections and coordinate systems; therefore, it is important to understand the map projection terminology.

Shape of Earth Shape of Earth is usually approximated by a mathematical model represented by an *ellipsoid* (also called a spheroid). A variety of cartographic ellipsoids have been designed to provide the best-fit properties for certain portions of the Earth's surface, for example, Clarke 1866 for North America, Bessel 1841 for several European countries, or the current WGS 1984 used worldwide. While the ellipsoid describes the shape of Earth by a relatively simple mathematical function, the *geoid*, an equipotential surface of the Earth's gravity, undulates due to the spatially variable distribution of the Earth's mass, see Figure 2.3. For map projections, the ellipsoids are usually sufficient for horizontal positioning; however, the geoid has to be used for high accuracy elevation calculations.

Geodetic or map datum A set of constants specifying the coordinate system used for calculating the coordinates of points on Earth is called a *geodetic datum.* Horizontal datums define the origin and orientation of a coordinate system used to calculate the horizontal coordinates (usually northing and easting). Vertical datums define the coordinate system origin for calculating the elevation coordinate, such as mean sea level. For maps to match, their coordinates must be computed using the same datum. Different datums mean a shift in the origin of the coordinate system, and that means a shift of the entire map.

Map projection To transform the curved Earth surface into a plane (flat sheet of paper or a computer screen), a *map projection* is used. Direct projection of a spherical object to a plane cannot be performed without distortion. The most common approach is to project the spheroid onto a *developable surface*, such as a cylinder or a cone that can be developed into a plane without deformation (tearing or stretching), see Figure 2.3. A large number of different projections have been designed with the aim to minimize the distortion and preserve certain properties (for a mathematical description refer to Bugayevskiy and Snyder, 2000:20-22). The *conformal* projection preserves angles (shapes for small areas) and is often used for navigation and national grid systems. The *equidistant* projection preserves certain relative distances and is used for measurement of length. The *equivalent* projection preserves area and is used for measurement of areas. Each of the properties (angle, distance, area) is preserved at the expense of the others. The map projection is usually selected depending on the application because there is no perfect solution to the projection problem. Most coordinate systems used for land surface mapping use conformal projections.

The developable surfaces can either touch the spheroid (tangent case) or intersect it (secant case). The most commonly used surfaces are a cylinder (*cylidrical* projection), a cone (conic projection), and a plane (*azimuthal* projection). The points or lines where the developable surface touches or intersects the spheroid are called *standard points* and *standard lines* with zero distortion (e.g. standard parallel for a tangent cone or two standard parallels for a secant cone). That means that the projected maps do not have uniform scale for the entire area, and that the true map scale is preserved only along the standard lines. To minimize distortions, some projections reduce the scale along the standard parallel(s) or central meridian(s). This is expressed as a *scale factor* smaller than 1.0 in the definition of such a projection.

Transverse projections use developable surfaces rotated by 90° so that the standard (tangent) line is a meridian called *central meridian* instead of a standard parallel. *Oblique projections* may use any rotation defined by azimuth where *azimuth* is an angle between a map's central line of projection and the meridian it intersects, measured clockwise from north. Snyder (1987) provides an excellent manual on map projections with map examples for many important projections.

Coordinate system To accurately identify a location on Earth, a *coordinate system* is required. It is defined by its origin (e.g., prime meridian, datum), coordinate axes (e.g. x, y, z), and units (angle: degree, gon, radiant; length: meter, feet). The following general coordinate systems are commonly used in GIS:

- *geographic* (global) coordinate system (latitude-longitude);
- *planar (cartesian) georeferenced* coordinate system (easting, northing, elevation) which includes projection from an ellipsoid to a plane, with origin and axes tied to the Earth surface;
- *planar non-georeferenced* coordinate system, such as image coordinate system with origin and axes defined arbitrarily (e.g. image corner) without defining its position on Earth.

Note that for planar georeferenced systems *false easting* and *false northing* may be used. These are selected offset constants added to coordinates to ensure that all values in the given area are positive.

For mapping purposes, each country has one or more *national grid systems.* Information about national grid systems can be obtained from the national cartographic institutes or from the ASPRS Web site[7]. A national grid system is defined by a set of parameters such as ellipsoid, datum, projection, coordinate system origin and axes, etc. Examples of worldwide and national grid systems are UTM (Universal Transverse Mercator), Gauss-Krüger, Gauss-Boaga, or State Plane. Information about the grid system used to georeference digital geospatial data is a crucial component of the metadata and allows the user to integrate and combine data obtained from different sources.

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[7] Information about national grid systems:
- ASPRS – Grids & Datums, `http://www.asprs.org/resources/grids/`
- European coordinate systems, `http://www.mapref.org`
- A comprehensive, general list of projection transformations is available at `http://www.remotesensing.org/geotiff/proj_list/`

2.2.2 Common coordinate systems and datums

Geographic coordinate system: latitude-longitude The most common coordinate system used for global data is the spherical coordinate system which determines the location of a point on the globe using latitude and longitude. It is based on a grid of meridians and parallels, where *meridians* are the longitude lines connecting the north and south poles and *parallels* are the latitude lines which form circles around the Earth parallel with the *equator*. The longitude of a point is then defined as an angle between its meridian and the *prime meridian* (0°, passing through the Royal Observatory in Greenwich, near London, UK). The latitude of a point is defined as an angle between the normal to the spheroid passing through the given point and the equator plane. The longitude is measured 0-180° east from prime meridian and 0-180° west, where 180° longitude is the international date line. Latitude is measured 0-90° north and 0-90° south from equator.

Geographic coordinates can be expressed in decimal degrees or sexagesimal degrees. Decimal values of west (W) and south (S) are expressed as negative numbers, north (N) and east (E) as positive numbers (e.g. Murcia, Spain: -1.1333°, 37.9833°). Values given in sexagesimal system always use positive numbers together with N, S, E, W (Murcia, Spain: 1:07:59.88W, 37:58:59.88N). It is not difficult to convert between these notations, see the GRASS Wiki[8].

Universal Transverse Mercator Grid System The Universal Transverse Mercator (UTM) Grid System is used by many national mapping agencies for topographic and thematic mapping, georeferencing of satellite imagery and in numerous geographical data servers. It applies to almost the entire globe (area between 84° N and 80° S). The pole areas are covered by the Universal Polar Stereographic (UPS) Grid System, please refer to Robinson et al. (1995).

UTM is based on a Transverse Mercator (conformal, cylindrical) projection with strips (zones) running north-south rather than east-west as in the standard Mercator projection. UTM divides the globe into 60 zones with a width of 6° longitude, numbered 1 to 60, starting at 180° longitude (west). Each of these zones will then form the basis of a separate map projection to avoid unacceptable distortions and scale variations. Each zone is further divided into strips of 8° latitude with letters assigned to from C to X northwards, omitting the letters I and O, beginning at 80° south (Robinson et al., 1995:101). For example, Trento (Italy; 11.133E, 46.067N) belongs to UTM zone 32, strip T. A conversion script from latitude-longitude to UTM zone/strip is available from the GRASS Wiki[9].

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[8] GRASS Wiki, Converting degree notations,
`http://grass.gdf-hannover.de/wiki/Convert_degree`

[9] Download section in the GRASS AddOns Web site,
`http://grass.gdf-hannover.de/wiki/GRASS_AddOns`

The origin of each zone (central meridian) is assigned an easting of 500,000m (false easting, Maling, 1992:358). For the northern hemisphere the equator has northing set to zero, while for the southern hemisphere it has northing 10,000,000m (false northing). To minimize the distortion in each zone, the scale along the central meridian is 0.9996, leading to a secant case of the Transverse Mercator projection with two parallel lines of zero distortion. Note that UTM is used with different ellipsoids, depending on the country and time of mapping.

For GIS applications, it is important to realize that each UTM zone is a different projection using a different system of coordinates. Combining maps from different UTM zones into a single map using only one UTM zone (which can be done relatively easily using GIS map projection modules) will result in significant distortion in the location, distances and shapes of the objects that originated in a different zone map and are outside the area of the given zone. To overcome the problem, a different coordinate system should be used and the data re-projected. For a quick reference, you can find the UTM zone numbers in the Unit 013 "Coordinate System Overview" of the NCGIA Core Curriculum in GIS.[10]

Lambert Conformal Conic Projection based systems The Lambert Conformal Conic (LCC) projection is one of the most common projections for middle latitudes. It uses a single secant cone, cutting the Earth along two standard parallels or a tangent cone with a single standard parallel. When working with LCC based coordinate systems, the following parameters have to be provided: the standard parallel(s) (one or two), the longitude of the central meridian, the latitude of projection origin (central parallel), false easting and, sometimes, false northing (you may recall that false easting and northing are shifts of the origin of the coordinate system from the central meridian and parallel).

State Plane Coordinate System The State Plane Coordinate System used by state mapping agencies in the USA is based on different projections depending on the individual state shape and location, usually LCC or a Transverse Mercator with parameters optimized for each state. Various combinations of datums (NAD27, NAD83) and units (feet, meters) have been used, so it is important to obtain all relevant coordinate system information (usually stored in the metadata file) when working with the data georeferenced in the State Plane Coordinate System. GIS projection modules often allow to define the State Plane system by providing the name of the state and the county, however, the parameters should always be checked, especially when working with older data.

[10] Unit 013 Coordinate System Overview in the NCGIA Core Curriculum in GIS, `http://www.ncgia.ucsb.edu/education/curricula/giscc/units/u013/u013.html`

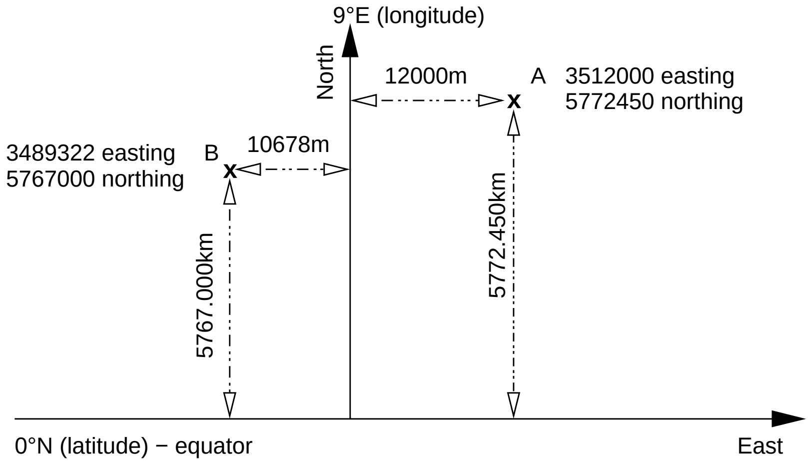

Fig. 2.4. Example for the Gauss-Krüger Grid System with two points A and B

Gauss-Krüger Grid System The Gauss-Krüger Grid System is used in several European and other countries. It is based on the Transverse Mercator Projection and the Bessel ellipsoid. The zones are 3° wide, leading to 120 strips. The zone number is divided by 3 according to longitude of central meridian. Adjacent zones have a small overlapping area. The scale along the central meridian (scale factor) is 1.0.

Figure 2.4 illustrates the coordinate system, the northing values are positive north from the equator, the easting values are measured from the central meridian. To avoid negative values, a false easting of 500,000m is defined in addition to the third of the longitude of the central meridian. For example, the false easting for the 9° E central meridian is 3,500,000m ($9/3 = 3$, value composed with 500,000m to 3,500,000m).

North American and European Datums In general, a large number of georeferencing datums exists, here we focus on three examples. The North American Datum 1983 (NAD83) is a geodetic reference system which uses as its origin the Earth's center of mass, whereas the old North American Datum 1927 (NAD27) had a different origin, making it useful only in North America. GPS receivers which are mostly based on the WGS84 datum (other local datums can be selected in the GPS receiver's menu) also use the Earth's center of mass as their system's origin.

When using maps based on different datums, a datum transformation to a common datum is required. For example, a change from NAD27 to NAD83 system leads to a shift for the entire map. Overlapping maps based on different datums of the same region would not co-register properly without datum transformation. In the continental United States, a few common assignments between datums and ellipsoids are in use: NAD27 datum with Clarke 1866 ellipsoid, NAD83 datum with GRS80 ellipsoid, and WGS84 datum with WGS84 ellipsoid.

It is important to know that the NAD27 and NAD83 datums are 2D horizontal datums used for horizontal coordinates (easting and northing). Separate vertical datums used with these systems are NGVD29 and NAVD88. GRASS does not handle yet separate vertical datums, so these transformations need to be done outside GRASS. WGS84 is a 3D datum (x, y and height).