Geodesy

W E Featherstone
Western Australian Centre for Geodesy, Curtin University of Technology, Perth, Australia, *W.Featherstone@curtin.edu.au*

Geodesy involves the theory and measurement of the size, shape and gravity field of the Earth. Modern geodesy is also concerned with temporal (time) variations in these quantities, notably through contemporary observations of geodynamic phenomena such as plate tectonics. Geodesy is a branch of applied mathematics that forms the scientific basis of all positioning and mapping.

In relation to GIS, geodesy provides the fundamental framework for accurate positions on or near the Earth's surface (georeferencing). Any soundly georeferenced GIS database should be based on appropriate geodetic datums (defined later), and positions displayed in terms of a map projection best-suited to the purpose at hand. As such, geodesy underpins GIS in that it provides a sound and consistent framework for the subsequent analysis of spatial data. GIS databases that do not have a sound geodetic basis will be of far less utility than those that do.

Numerous other (unknown and/or untraceable) sources give definitions complementary that distilled above. Examples are: the science of measuring the size, shape and gravity field of the Earth; scientific discipline concerned with the size and shape of the Earth, its gravitational field, and the location of fixed points; the science related to the determination of the size and shape of the Earth (geoid) by direct measurements; science concerned with surveying and mapping the Earth's surface to determine, e.g., its exact size, shape and gravitational field; a branch of applied mathematics concerned with the determination of the size and shape of the Earth (geoid); applied mathematics dealing with the measurement, curvature and shape of the Earth, rather than treating it as a sphere; the scientific discipline that deals with the measurement and representation of the Earth, its gravitational field and geodynamic phenomena (polar motion, Earth tides and crustal motion) in three-dimensional time varying space; the scientific study of the Earth's surface by surveying (especially by satellite) and mapping in order to determine its exact shape and size, and to measure its gravitational field; geodesy is primarily concerned with positioning and the gravity field and geometrical aspects of their temporal variations.

The classical definition, according to Helmert (1880), is: "Geodesy is the science of measuring and portraying the Earth's surface". Since then, the scope of geodesy has broadened (Vaníček and Krakiwsky, 1986): "Geodesy is the discipline that deals with the measurement and representation of the Earth, including its gravity field, in a three-dimensional time-varying space".

Since geodesy is now quite a diverse discipline, it is often broken down into subclasses. In this author's opinion, the four key pillars of modern geodesy are (not in any order of preference):

1. **Geophysical Geodesy**: geodetic techniques are used to study geodynamic processes, such as plate tectonic motions, postglacial rebound (now called glacial isostatic adjustment) or variations in Earth rotation and orientation.

2. **Physical Geodesy**: the observation and use of gravity measurements (from ground, air and space) to determine the figure of the Earth, notably the geoid, which involves the formulation and solution of boundary-value problems.

3. **Geometrical/Mathematical Geodesy**: computations, usually on the reference ellipsoid, to yield accurate positions from geodetic measurements, including map projections, which involves aspects from differential geometry.

4. **Satellite/Space Geodesy**: determination of the orbits of satellites (hence inferring the gravity field) or for determining positions on or near the Earth's surface from ranging measurements to navigation satellites.

On the other hand, the international scientific organisation in geodesy, the International Association of Geodesy (IAG; http://www.iag-aig.org/), has four main commissions, comprising

1: **Reference Frames**

a. Establishment, maintenance and improvement of geodetic reference frames
b. Advanced terrestrial and space observation technique development
c. International collaboration for the definition and deployment of networks of terrestrially-based space-geodetic observatories
d. Theory and coordination of astrometric observation for reference frame definition and realisation
e. Collaboration with space-geodesy/reference-frame-related international services, agencies and organisations

2: **Gravity Field**

a. Terrestrial, marine, and airborne gravity measurements (gravimetry)
b. Satellite-based gravity field observations
c. Global and regional gravity field modelling
d. Time-variable gravity field observation
e. Geoid and quasigeoid determination
f. Satellite orbit modelling and determination

3: **Earth Rotation and Geodynamics**

a. Earth orientation (Earth rotation, polar motion, nutation and precession)
b. Earth tides
c. Tectonics and crustal deformation
d. Sea surface topography and sea-level change
e. Planetary and lunar dynamics
f. Effects of the Earth's fluid layers (e.g., postglacial rebound, surface loading)

4: **Positioning and Applications**

a. Terrestrial- and satellite-based positioning systems development
b. Navigation and guidance of platforms
c. Interferometric laser and radar applications (e.g., synthetic aperture radar)
d. Applications of geodetic positioning using 3D geodetic networks (passive and active), including monitoring of deformations
e. Applications of geodesy to engineering
f. Atmospheric investigations using space-geodetic techniques

Clearly, there is overlap amongst these four IAG Commissions, but they are consistent with the broad definition and goals of modern geodesy given earlier. In addition, the IAG operates or endorses a number of Services, recognising that geodesy is a global science that requires collaboration among various organisations to achieve its goals. The current IAG Services are:

- IERS (International Earth Rotation and Reference Systems Service)
- IGS (International GPS Service)
- ILRS (International Laser Ranging Service)
- IVS (International VLBI Service for Geodesy and Astrometry)
- IGFS (International Gravity Field Service)
- IDS (International DORIS Service)
- BGI (International Gravimetric Bureau)
- IGES (International Geoid Service)

- ICET (International Centre for Earth Tides)
- PSMSL (Permanent Service for Mean Sea Level)
- BIPM (Bureau International de Poids and Measure - time section)
- IBS (IAG Bibliographic Service).

Each has its own webpage describing the geodetic products and services offered.

Geodetic measurement techniques

Traditionally, geodetic measurements over large areas involved ground-based measurements of triangulation, distance measurement and differential levelling. Triangulation involves the measurement of angles and directions, originally by theodolite, but now by electronic total station. Electronic distance measurement (EDM) provides scale and involves timing the travel of an electromagnetic signal to and from a reflector. Differential levelling involves measuring the height difference between two graduated staves. All instruments must be properly calibrated against agreed national and international standards.

In the post-satellite era, terrestrial-geodetic measurements have been supplemented with (and sometimes superseded by), generally more precise, space-based observations from Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR) and satellite navigation systems such as the US Global Positioning System (GPS), Russian GLONASS and French DORIS. Europe will start deployment of its Galileo satellite navigation system in 2008. Collectively, these are called Global Navigation Satellite Systems (GNSS).

VLBI uses radio telescopes to measure the difference in arrival times between radio signals from extragalactic sources to derive millimetre-precision baseline lengths over thousands of kilometres. SLR uses reflected laser light to measure the distance from the ground to a satellite equipped with corner-cube mirrors to give absolute positions of the ground telescope. GPS, GLONASS and Galileo use timed signals from radionavigation satellites to compute positions by resection of distances. As these systems are located on most continents, a truly global reference frame can be created.

A more recent geodetic measurement technique is interferometric synthetic aperture radar (InSAR). Satellite-borne radars measure heights of the topography or changes in the topography between two images. Though less accurate than levelled height measurements, InSAR can measure heights over large areas. An example is global mapping from the Shuttle Radar Topography Mapping (SRTM) experiment. InSAR has also been used to detect surface position changes over wide areas, such as after a large earthquake (e.g., Landers, California, in 1994).

Gravity is measured is a variety of ways: absolute gravimeters time free-falling proof masses over a known distance; relative gravimeters essentially use differences in spring lengths to deduce gravity variations from place to place. Absolute gravimetry forms a framework for the (cheaper and easier) relative gravity measurements. Relative gravimetry is also used at sea (marine gravimetry) or in the air (airborne gravimetry), where careful stabilisation is needed to separate gravitational and vehicle accelerations. Global gravity is measured from the analysis of artificial Earth satellite orbits, and recent dedicated satellite gravimetry missions (CHAMP, GRACE, GOCE) are making significant contributions, including measuring the time-variable gravity field. Superconducting gravimeters are also used in geodynamics and tidal studies because of their low drift rates.

Satellite altimetry is a geodetic measurement technique over the oceans. Timed radar signals are bounced from the sea surface back to the satellite. Knowing the position of the satellite (from ground-based SLR tracking or space-based GPS orbit determination), the height of the instantaneous sea surface can be deduced. This has allowed for improved models of the ocean tides. When averaged to form a mean sea surface, marine gravity can be derived, giving detailed coverage of the marine gravity field. Bathymetry can also be inferred from the mean sea surface and gravity field.

Clearly geodetic observation techniques have evolved to a large reliance on space-based technologies. As such, the global science of geodesy is now permitting more detailed and larger scale observations of the Earth system, the most notable being global change though sea level change studies from satellite altimetry and gravimetry and geodynamics (plate tectonics and glacial isostatic adjustment) by repeated VLBI, SLR, GNSS and InSAR campaigns.

Horizontal and vertical geodetic datums

A geodetic datum is a point-wise definition of accurately defined coordinates of solidly seated ground monuments on the Earth's surface, which are determined from geodetic measurements. Horizontal coordinates are usually supplied in terms of geodetic latitude and longitude with respect to a particular geodetic reference ellipsoid (and datum). Vertical coordinates are supplied in terms of heights above local mean sea level determined by tide gauges. The geodetic reference ellipsoid is flattened towards the poles with an equatorial bulge, and thus better reflects the true figure of the Earth than a simple sphere. Widely accepted global reference ellipsoids are GRS80 and WGS84, but there are numerous local ellipsoids over various countries.

Numerous corrections have to be applied to geodetic measurements to account for errors such as atmospheric refraction and the curvature of the Earth. Corrections must also be made for spatial variations in the Earth's gravity field. To minimise geodetic observation and data reduction errors, a least-squares adjustment is used to compute the positions and estimates of the errors in those positions. This forms the geodetic datum: a horizontal datum defines geodetic coordinates at ground monuments with respect to a particular reference ellipsoid; a vertical datum defines heights at ground monuments with respect to local mean sea level.

Historically, horizontal geodetic datums derived from terrestrial-geodetic measurements have been established in a country, continent or region. For instance, Australia had the Australian Geodetic Datum. Vertical datums are established separately from horizontal datums, which is a product of the different measurement techniques and principles (a vertical datum should correctly describe the flow of fluids). For instance, Australia has the Australian Height Datum. In some cases, the same ground monuments will have coordinates on both datums.

Terrestrial- and space-geodetic measurements are now combined to form 3D geodetic datums, but vertical datums based on mean sea level are still in use because the reference ellipsoid is unsuitable for properly describing fluid flows. Therefore, corrections for gravity, by way of a geoid model, are needed to transform heights from space-based positioning to heights on a mean sea level-based local vertical datum. The geoid is loosely speaking the mean sea level surface that undulates with respect to the geodetic reference ellipsoid by approximately 100 metres due to changes in gravity. The use of space-geodetic measurements (VLBI, SLR, GNSS) has allowed the establishment of global geodetic datums, which are now superseding terrestrial geodetic datums in some countries. For instance, Australia now uses the Geocentric Datum of Australia, but the Australian Height Datum is retained.

Through the auspices of the IAG, the international terrestrial reference frame (ITRF) is the *de facto* global geodetic datum. With additional measurements and improved computational procedures, coupled with the need to account for tectonic plate motion, several versions of the ITRF have been realised over the years, the most recent being ITRF2005. ITRF provides both 3D positions and velocities for each point, so as to account for plate-tectonic motion. As such, epochs are used to specify the position at a particular time, e.g., ITRF1994, epoch 2000.0. Cartesian coordinates are usually specified, but these are easily transformed to geodetic latitude, longitude and height.

Geodetic coordinate transformations

With the plethora of different geodetic datums and their associated reference ellipsoids (well over 100 different geodetic datums and ellipsoids are in use around the world), there is the need to transform coordinates among them. This is especially the case when positioning with GNSS in relation to existing maps and charts. A common cause of error is because of lay misunderstanding of the importance of geodetic datums, which can result in positioning errors of over a kilometre in some extreme cases. Therefore, any serious user or producer of georeferenced spatial data must also know the geodetic datum being used for those positions.

Once the datum and ellipsoid are defined, it is a relatively straightforward to mathematically transform coordinates between horizontal geodetic datums. However, several various different mathematical models and sets of transformation parameters are available, all with different levels of transformation accuracy. Most often, the national geodetic agency (e.g., Geoscience Australia) will be able to provide the recommended transformation method for its jurisdiction. This also applies to the appropriate geoid model for transforming GPS-derived ellipsoidal heights to the local vertical datum.

Otherwise, the US National Geospatial Intelligence Agency (NGA) provides simple transformation parameters (3D origin shift) for most geodetic datums as well as a global geoid model.

In all cases, metadata on the transformation methods (i.e., mathematical models and parameter values) should be stored/archived together with the transformed coordinates, so that subsequent users can trace back to the original data source. As geocentric (Earth-centred) datums have started to replace local horizontal geodetic datums, this is becoming a routine necessity. Likewise, the geoid model used to transform GNSS-derived heights to a local vertical datum should be noted, as geoid models change over time. Basically, clear documentation is needed to preserve the geodetic integrity of the geospatial data.

Map projections

GIS users will usually want to display spatial data on a flat screen. Over two millennia, several hundred different map projections have been devised to faithfully portray positions from the curved Earth on a flat surface. Basically, the geodetic latitude and longitude are converted to an Easting and Northing through a mathematical projection process. However, any map projection causes distortion in area, shape and scale, and various projections have been designed to cause least distortion in one of these, usually at the expense of the others. Therefore, a map projection that is best-suited to the purpose should be chosen (e.g., an equal area projection for displaying demographics or a conformal projection for preserving angles).

Map projection equations are normally quite complicated because we have to deal with the reference ellipsoid that curves differently in the north-south and east-west directions. Truncated series expansions are often used that usually allow computations at the millimetre level. Historically, map projections were simplified so as to facilitate practical computations. Nowadays, however, map projections can be efficiently computed, even on modestly powered hand calculators. Probably the most popular map projection for geodetic purposes is the Universal Transverse Mercator (UTM) projection.

There are different classes and aspects of map projection: the projection may be cylindrical (better for mapping equatorial regions), conical (better for mapping mid-latitude regions) or azimuthal (better for mapping polar regions); the aspect can be changed so that these classes can be adapted to a particular area. For instance, an oblique aspect may be used to map a country whose geography is not north-south or east-west oriented.

One final consideration when using map projections in GIS databases is to be sure to carefully specify the projection (or de-projection) methods used, as well as the reference ellipsoid and geodetic datum used. For instance, UTM Easting and Northing can be computed from geodetic latitude and longitude on any geodetic datum and using any reference ellipsoid, so the users must be sure the appropriate methods are used consistently and well-documented. It is very easy for an inexperienced GIS user to cause terrible confusion in a GIS database by not getting the geodetic principles right.

Concluding remarks

Geodesy is now a reasonably diverse and broad-ranging discipline. Essentially, it has evolved from the largely static study of the Earth's size, shape and gravity field to investigating time-varying changes to the whole Earth system. It has made significant contributions to mapping, engineering, surveying, geodynamics and sea level change studies. Nevertheless, it also provides the fundamental framework for georefencing in GIS databases, so it is important for GIS database managers and GIS data analysts to have an operational appreciation of geodesy (and to implement checking systems) to ensure that geospatial data are treated in a consistent geodetic framework.