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Digital Terrain Models

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Definition

Digital Terrain Model. Digital description of the terrain surface using a set of heights over 2D points residing on a reference surface

Introduction

A Digital Terrain Model (DTM) approximates a part or the whole of the continuous terrain surface by a set of discrete points with unique height values over 2D points. Heights are – in approximation - vertical distances between terrain points and some reference surface (e.g., mean sea level, geoid and ellipsoid) or geodetic datum. Mostly arranged in terms of regular grids, the 2D points are typically given as geodetic coordinates (latitude and longitude), or planar coordinates (North and East values). DTMs usually assign a single unique height value to each 2D point, so cannot describe vertical terrain features (e.g., cliffs). DTMs are therefore “2.5D” rather than truly 3D models of the terrain (Weibel and Heller, 1991).

Fig. 1. Left: DTM, Right DSM. Data obtained from airborne laser scanning, resolution 1 m, area covers 1000x1000 m and shows a part of Germanys high-speed train network between Nuremberg and Ingolstadt. Image courtesy Wolfgang Reinhardt and Walter Henninger (Munich).

While DTMs represent the bare ground of the terrain, a Digital Surface Model (DSM) describes heights of vegetation (e.g., trees) and of man-made features (e.g., buildings) too (Fig. 1). It is thus important to distinguish between DTM and DSM over vegetated or built areas. A closely related term is Digital Elevation Model (DEM), which is sometimes used synonymously with DTM, but often as an umbrella term to describe both DTM and DSM (Wood, 2008; Hutchinson and Galant, 2009; Shinagre and Kale, 2013). DEM is often used for elevation models from remote sensing (e.g., radar or photogrammetry). These models are rather DSM than DTM unless vegetation and building heights are removed.

The concept of DTM is not only limited to Earth's visible terrain surface. It also finds application in bathymetry (digital bathymetry models describing the geometry of the sea floor), polar geodesy (digital bedrock models to describe the rock below the ice sheets), and planetary sciences (digital elevation models of the planetary surfaces), among many other areas of application.

Representations

Common mathematical representations for DTMs include regularly spaced grids (2D raster or matrix form), irregularly distributed 2D points (variable point distances), 1D-profiles, contours (i.e., lines of constant heights), and Fourier series (Li et al., 2004). Triangulations of irregularly distributed 2D points, known as Triangulated Irregular Networks (TIN) allow incorporation of terrain break lines (ridges, valleys), and extreme locations (e.g., summits) to better represent the terrain, but are more complex to handle than gridded DTMs. Gridded DTMs are derived from TINs through computation of height values at 2D raster locations using some interpolation technique (e.g., fitting of linear or curved surfaces, least-squares prediction, kriging). With increasing spatial resolution, gridded DTMs tend to approximate break lines and extreme locations better, while containing more redundant information in flat terrain. DTMs are most commonly provided in terms of regularly spaced grids which allows simple data handling, manipulation and storage (cf. Li et al., 2004, El-Sheimy et al., 2005; Peckham and Gyozo, 2007). Another efficient but less common way to present a DTM is through a set of surface spherical harmonic coefficients computed from a high-resolution 2D raster. DTM heights at arbitrary locations are then obtained through series expansion of the coefficients. Currently, those spherical harmonic DTM representations reach spatial resolutions of about 2 km, equivalent to harmonic degree 10,800 (Balmino et al., 2012; Hirt and Rexer 2015).

Sources of DTM data

From a range of sources relying on ground-based, airborne and space-borne surveying techniques DTM data is available for parts and the whole of the Earth's surface at different spatial resolution. Traditional ground-based methods (e.g., Kennie and Petrie, 1990) are very accurate, but tedious, and therefore mostly limited to small areas. Field surveying based on tachymetry delivers terrain heights at selected locations. Satellite surveying techniques (GNSS) provide terrain heights at discrete locations, or along profiles (e.g., roads). GNSS heights are sometimes used as a check on DEMs from remote sensing. Another source of terrain heights are digitized contour lines from existing topographic maps.

Modern airborne- and space-borne sensors are considerably more efficient for terrain surface mapping than ground methods. This is because the terrain is sampled at a vast number of locations in little time, and the sensor movement in air or space allows mapping of regional or even global profiles. Important mapping sensors on flying platforms are (i) image-based (photogrammetry), (ii) laser-based (lidar), and (iii) radar-based (e.g., radar interferometry).

Photogrammetric methods (e.g., Baltsavias, 1999) use overlapping pairs of images showing the terrain from different angles (stereo principle). Stereoscopic processing yields terrain heights for ground points captured and identified in both images. Aerial photogrammetry is used for terrain mapping at national scale, and satellite-borne imagery (e.g., SPOT, ASTER or ALOS satellites) globally. Dense vegetation cover and clouds reduce the completeness of DTM data from photogrammetry.

To establish terrain heights with laser-based methods (lidar), travel time of short light pulses - emitted from ha laser measurement system and reflected by the ground – is measured. Rotating mirrors spread series of laser pulses into swaths allowing to sample terrain height profiles with high spatial resolution. Over vegetated areas, there are usually multiple return pulses (e.g., reflection at the top of the canopy and at the ground), which provide information on the bare ground elevation and vegetation height. Airborne lidar (airborne laser scanning, cf. Baltsavias, 1999) is a standard in generating highly-accurate and detailed regional DTMs and DSMs in an efficient manner. Space-borne lidar, deployed e.g., on the ICESAT satellite, is well-suited to obtain DTMs over the Earth's ice sheets. Similar technique used aboard planetary missions provided highest-resolution DTMs for Mars and Moon.

Different to lidar, radar-based techniques operate with microwave signals which are cloud-penetrating. Signal travel time, phase, of phase differences are used as measure. Commonly used radar variants are SAR (synthetic aperture radar) with increased imaging resolution through use of artificial apertures, and InSAR (interferometric SAR), where the stereo principle is applied with two nearby antennas recording the same radar pulse (Rabus et al., 2003). Differences in signal phases depend on the terrain height, so can be used to derive DTM data. In steep terrain, radar-based topographic mapping may produce voids in the DTM caused by so-called radar shadows or signal layover. The most prominent example for space-borne InSAR is the Shuttle Radar Topography Mission (SRTM). Radar systems are being operated aboard planes for special applications too, e.g., to obtain elevation data of the rock beneath Earth's ice-sheets. In a planetary context, radar was used to obtain a DTM of Venus, a permanently cloud covered planet.

Earth elevation products

Publically and freely available DEMs with continental or near-global coverage originate from space-borne topographic mapping missions, notably from the SRTM and ASTER missions. The characteristics of selected DEMs with near-global coverage are reported in Table 1.

The first near-global high-resolution DEM was acquired in the year 2000 from SAR interferometry carried out aboard the Space Shuttle (Rabus et al., 2003). The SRTM DEM covers most of Earth's land areas between 60°N-56°S. Originally produced at 1 arcsec (30 m) spatial resolution, the DEM data has been released at lower resolution level of 3 arcsec (90 m) to the public in 2003. Recently, USGS announced to release the SRTM data set at 1 arc-sec resolution globally. The initial SRTM release was subject by numerous voids in steep terrain, which were filled e.g., based on interpolation techniques, or auxiliary elevation data sets and published by CGIAR-CSI as version v4.1 (e.g., Jarvis et al., 2008). The most recent SRTM USGS release (v2.1) still contains voids.

A higher-resolution global DEM data set was released to the public by NASA/METI based on stereoscopic imagery from the ASTER satellite. The global ASTER DEM extends towards the pole regions (±83° latitude) at 1 arc-sec resolution. The current ASTER DEM release is GDEM2 (Tachikawa et al., 2011). It describes the terrain surface with mostly greater detail than SRTM, but is in places subject to artefacts such as diagonal stripes and peaks (e.g., Rexer and Hirt, 2014) which impede its direct use in some applications.

Table 1. Characteristics of selected near-global DEMs. Acronyms: NGA = National Geospatial Intelligence Agency, NASA = National Aeronautics and Space Administration, USGS = United States Geological Survey, METI = Ministry of Economy Trade and Industry (Japan), CGIAR CSI = Consortium for Spatial Information, DLR = Deutschen Zentrum für Luft- und Raumfahrt (Germany), SRTM = Shuttle Radar Topography Mission, ASTER = Advanced Spaceborne Thermal Emission and Reflection Radiometer, GDEM = Global Digital Elevation Model, JAXA = Japan Aerospace Exploration Agency

Mission/DTM product	**Institution**	**Coverage**	**Spatial Resolution**[*3]	**Source**
SRTM 1 arc-second global	NASA, NGA, USGS	60°N-56°S	1 arc-sec	http://earthexplorer.usgs.gov/
SRTM USGS v2.1	NASA, USGS, JPL	60°N-56°S	3 arc-sec	http://dds.cr.usgs.gov/srtm/
SRTM CGIAR CSI v4.1	CGIAR-CSI	60°N-56°S	3 arc-sec	http://srtm.csi.cgiar.org/
ASTER-GDEM2	METI, NASA	83°N-83°S	1 arc-sec	http://asterweb.jpl.nasa.gov/gdem.asp
Tandem-X/ World-DEM	DLR	87°N-87°S or more	3 arc-sec[*1]	not yet available
ALOS World 3D	JAXA	82°N-82°S or more	1 arc-sec[*2]	not yet available

[*1] 0.4 arc-sec resolution as commercial product, [*2] 0.15 arc-sec as commercial product, [*3] An angle of 1 arcsec equates to about 30 m in North-South direction on the Earth's surface

It is important to note that the SRTM or ASTER DEMs cannot be considered as pure DTMs. In case of ASTER the underlying optical stereo methods applied did not probe the bare ground over built or vegetated areas, but rather the top of terrain features (DSM). In case of SRTM, radar reflections cannot be unambiguously attributed to either the ground or the top of canopy, which is why SRTM is probably best characterized as mixed DSM/DTM. Overall both the SRTM and ASTER DEMs represent terrain heights at the 10 m accuracy level. The accuracy, however, can be better in non-vegetated and flat terrain (few metres), while being worse in mountain areas (e.g., Rexer and Hirt, 2014).

Using improved InSAR technology, the TanDEM-X satellite mission (Krieger et al., 2007) has now mapped the Earth's global topography with a spatial resolution of 0.4 arc-sec (about 12 metres). While TanDEM-X is a commercial mission, a down-sampled elevation model (WorldDEM) with 3 arc-sec resolution (commensurate to SRTM) and global coverage is intended to become freely available for science. As a commercial product, a pure DTM (with building heights and vegetation removed) will be produced. Further global DEM data sets can be expected to become available from remote sensing in the future. As an example, a new 3D model of the Earth's surface of up to 0.15 arc-sec (5 m) resolution will be generated from optical stereoscopy carried out aboard the ALOS satellite (ALOS World 3D, Tadano et al., 2014).

A number of composite DEMs exist that describe Earth's surface in the absence of water and ice masses, by providing bathymetric depths over the oceans and major lakes, and elevations of bedrock over Antarctica and Greenland. Examples include NOAA's ETOPO1 (60 arc-sec global resolution) and Scrippts Institution of Oceanography's SRTM_30PLUS (30 arc-sec global resolution, no ice information).

Complementary to global terrain models from remote sensing, surveying agencies of many countries have generated DTMs from a composite of data sources, e.g., ground surveys, contour scans, and airborne photogrammetry. These national models are mostly commercial products. For parts of some countries and regions, extremely detailed DTMs have been produced from airborne laser scanning with often 1-meter-resolution and sub-m-precision.

Applications

Terrain models play a fundamental role in geosciences and engineering, and have numerous applications. They can be used to calculate derived quantities, such as volumes, slope, curvature, sun exposure, hill shade, contours, visibility from given sites, drainage, and gravitational attraction. Application examples for DTM include its use as a base layer in geographic information systems (GIS), e.g. for planning of engineering structures (roads, railways, canals), hydrology (drainage and catchment area analysis), coastal protection (inundation), mass movements in mountain areas, rendering visualisations and topographic maps, planning of radio networks and alternative energy power plants, and rectification of photogrammetric imagery (orthophotos).

In the narrower field of gravity field modelling and physical geodesy, DTM data is a pivotal data source providing geometry information of the topographic masses. Using gravity forward modelling techniques, the gravitational attraction of the masses is computed from DTM data, and can be (i) subtracted from observed gravity values to highlight signatures of mass anomalies in the Earth's interior, (ii) used as reduction in geoid determination, or (iii) utilized to predict a detailed gravity field over otherwise less surveyed areas. For these applications, the availability of DTM rather than DSM data is important.

Summary

DTMs, conceptionally introduced more than half a century ago, are today in wide use in geodesy and beyond to approximate the Earth's relief for a broad range of applications. DTMs are publically available with near-global coverage from satellite-based mapping missions (notably SRTM and ASTER) at 1 to 3 arc-sec resolution and 10-20 m accuracy. In the near future, new commercial DTMs from the TanDEM-X and ALOS missions will provide more detailed terrain information than currently available. At a national level, DTMs exist for many countries at varying resolution, mostly from ground-based, airborne lidar and photogrammetric surveys. On a planetary scale, high-resolution DTM information is available for Moon, Mars, Venus and other bodies.

Cross references

Gravity Forward Modelling, Topographic Effects, Regional Gravity Field Determination

Bibliography

Balmino, G., Vales, N., Bonvalot S., and Briais, A. 2012. Spherical harmonic modelling to ultra-high degree of Bouguer and isostatic anomalies. J. Geod., 86, 499-520.

Baltsavias, E.P., 1999. A comparison between photogrammetry and laser scanning. ISPRS Journal of Photogrammetry & Remote Sensing, 54, 83-94.

El-Sheimy, N., Valeo, C., and Habib, A., 2005. Digital Terrain Modeling: Acquisition, Manipulation And Applications. Norwood: Artech House.

Hirt, C., Rexer, M., 2015. Earth 2014: 1 arc-min shape, topography, bedrock and ice-sheet models - available as gridded data and degree-10,800 spherical harmonics. International Journal of AppliedEarth Observation and Geoinformation, 39, 103–112.

Hutchinson, M.F., and Gallant, J.C., 2005. Representation of Terrain. In Longley, P.A. et al. (ed.) Geographical Information Systems: Principles, Techniques, Management and Applications, Hoboken: John Wiley and Sons.

Jarvis A., Reuter H.I., Nelson A. and Guevara, E. 2008. Hole-filled SRTM for the globe Version 4. Available from the CGIAR-CSI SRTM 90m database. http://srtm.csi.cgiar.org

Kennie, T.J.M., and Petrie, G., 1990. Digital terrain modelling. In Kennie, T.J.M., and Petrie, G., (ed). Engineering Surveying Technology, Oxon: Taylor and Francis.

Krieger, G. A. Moreira, et al., 2007. TanDEM-X: a satellite formation for high resolution SAR interferometry. IEEE Trans. Geosci. Remote Sens., 45, 3317–3341.

Li, Z., Zhu, C., and Gold, C., 2004. Digital Terrain Modeling: Principles and Methodology. Boca Ration: CRC Press.

Peckham, R.J., and Gyozo, J., (Eds) 2007. Digital Terrain Modelling, Development and Applications in a Policy Support Environment. New York: Springer.

Rabus, B., Eineder, M., Roth, A., and Bamler, R., 2003. The Shuttle Radar Topography Mission – A New Class of Digital Elevation Models Acquired by Spaceborne Radar. ISPRS Journal of Photogrammetry & Remote Sensing, 57, 241-262.

Rexer, M., and Hirt, C., 2014. Comparison of free high resolution digital elevation data sets (ASTER GDEM2, SRTM v2.1/v4.1) and validation against accurate heights from the Australian National Gravity Database; Australian Journal of Earth Sciences, 61, 213-226.

Tachikawa, T., et al., 2011. ASTER Global Digital Elevation Model Version 2 – Summary of Validation Results,https://www.jspacesystems.or.jp/ersdac/GDEM/ver2Validation/Summary_GDEM2_validation_report_final.pdf.

Tadono, H., Ishida, H., et al., 2014. Precise global DEM generation by ALOS PRISM. ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume II-4, 71-76.

Shingare, P.P., Kale, S.S., 2013. Review on Digital Elevation Model. International Journal of Modern Engineering Research, 3: 2412-2418.

Weibel, R., and Heller, M., 1991. Digital Terrain Modelling. In Maguire, D.J. et al. (ed.) Geographical Information Systems: Principles and Applications. London: Longman.

Wood, J., 2008. Digital elevation model (DEM). In Kemp, K. (ed.), Encyclopedia of geographic information science. Thousand Oaks, CA: SAGE Publications, pp 107-110.