Geographic Information Technology Training Alliance (GITTA) presents:

Terrain Analysis

Responsible persons: Friedjoff Trautwein, Helmut Flitter, Marco Hugentobler, Patrick Lüscher, Philipp Weckenbrock, Robert Weibel, Suzette Hägi

Table Of Content

1. Terrain Analysis 2
  1.1. Extraction of topographic information 3
    1.1.1. Derivative information 4
    1.1.2. Exercise 7
  1.2. Geomorphometry 8
    1.2.1. Slope 8
    1.2.2. Aspect 10
    1.2.3. Curvature 11
    1.2.4. Discussion 12
  1.3. Visibility analysis 13
    1.3.1. Calculation of visibility 13
    1.3.2. Self Assessment 16
  1.4. Hillshade 17
    1.4.1. Shading methods 17
  1.5. Summary 19
  1.6. Recommended Reading 20
  1.7. Bibliography 21

1. Terrain Analysis

Three dimensional views of digital terrain models are mainly known from flight simulators or digital atlases. In this lesson you will learn about the information that can be derived from digital terrain models. These information products can be used in different ways and they can also be combined with non-terrain information. In the first unit, an overview of possible information which can be derived from digital terrain models will be provided. In unit 2 you will learn about slope, aspect and curvature and how they can be derived from a raster or linear interpolated triangular irregular networks (TIN). You will also learn about examples of geomorphometry. Visibility analysis is the topic of unit 3. Using specific methods (for raster based, as well as linear interpolated TINs) visibility analysis allows you to determine whether a point is visible from a given location. In unit 4 you learn how to calculate the reflection and how to create a shaded relief map from a raster.

Learning Objectives

- You get an overview of the most important information products that can be derived from digital terrain models.
- You know the basic methods to derive the most important parameters of geomorphometry (slope, aspect and curvature). You know the fundamental techniques to calculate the visibility from a point in raster and linear TINs.
- You know how the visibility of a point in a grid or linear TIN based digital terrain model is calculated.
- You know the most important application of the visibility analysis.
- You know the principles of relief shading and are able to calculate the reflection of a raster cell.

1.1. Extraction of topographic information

The terrain plays an important role in many spatial models. In a GIS, the information about altitude is stored in digital terrain models. In this unit, we learn how to derive information from digital terrain models and how, and in which context, it is used.

The terrain plays an important role in many spatial model (Photo: Ross Purves)

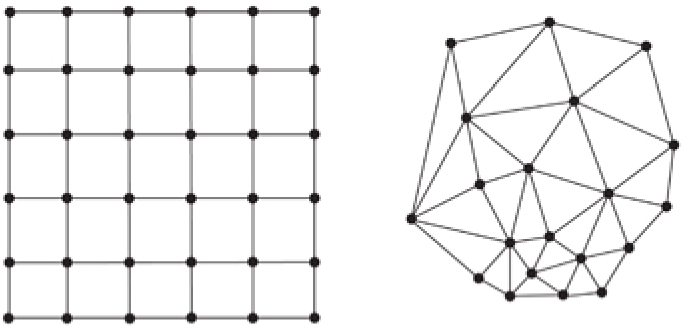
Grid vs. TIN

In a digital terrain model, altitude values are usually organized in one of these data structures:

- Grid
- TIN

The structures of grids are similar to raster data sets. Each rectangular grid cell has the same size. The altitude is stored in each of these grid cells. This data structure is the most widely used structure, due to its simplicity and easily implemented algorithm. However, the disadvantage of a grid is that density cannot be adjusted to the complexity of the terrain. For that reason there are often too many data used for the representation of simple terrains.

TINs consist of irregularly distributed points. The triangles are built up on these points. This data structure allows for the efficient storage of terrain information; the triangulation allows a variable density and distribution of points. It can be adapted to more complex terrain (more data points at complex terrains and fewer points in flat areas of the terrain). It is more complicated to implement these algorithms than to implement algorithms based on raster data.

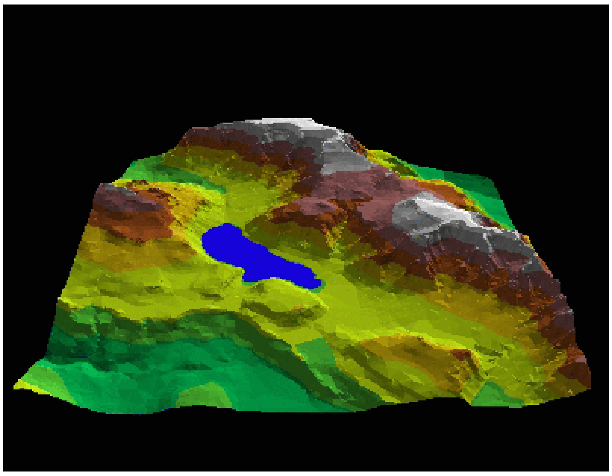
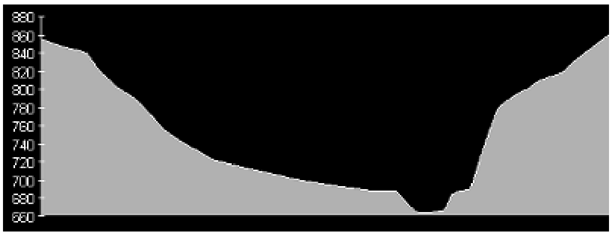


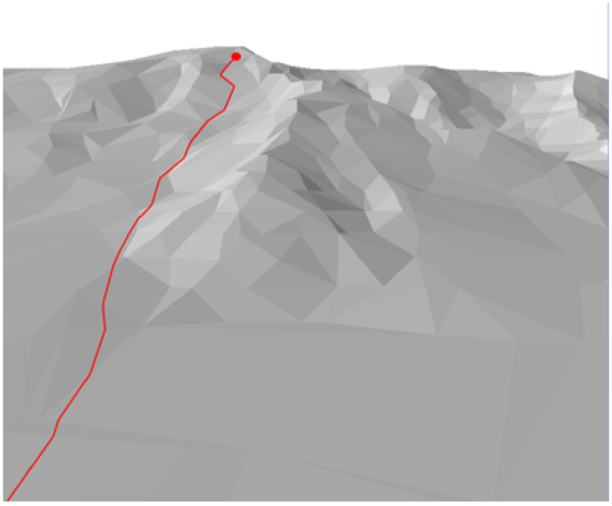
Grid (left side) and TIN (right side)

1.1.1. Derivative information

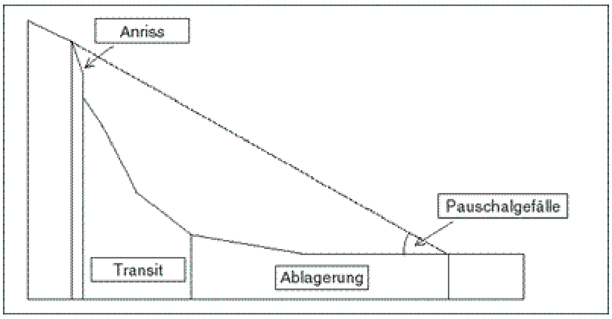
Examples of derived information

Digital terrain models contain more information than the altitude of the points. There is a lot of implicit information, which is not stored explicitly. It can be extracted using appropriate methods. Have a look at the following perspective illustration of a digital terrain model for the area around Türlersee (near Zürich, Switzerland). The following images illustrate the information which can be derived from digital terrain models.

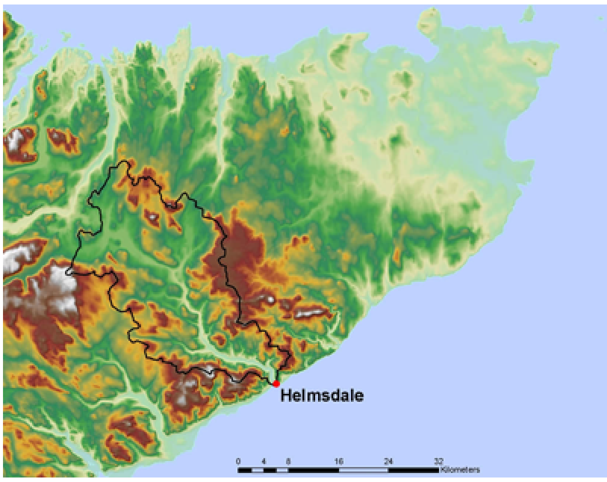
	Digital terrain model of the area of Türlersee (Hugentobler 2000).
	The profile between two points can be derived from a digital terrain model. Such profiles are relevant in many engineering applications, e.g. in street planning or tunnel construction.



The line of greatest slope is a curve following the steepest slope where water would drain (starting at a given point). Such lines are used to model ice debris and rock falls, as well as for the calculation of catchment areas.



The slope (gradient) is the slope between two points in the terrain. It is mainly used for the modeling of gravitational processes (rock fall, ice debris).



Catchments are an important component in many hydrological, geomorphologic and environmental GIS applications.

The table below provides an overview of the information which can be derived from digital terrain models. To learn more about elevation, slope, plan curvature and profile curvature, have a look at unit 1.2. To learn more about intervisibility and the calculation of viewsheds, have a look at unit 1.3.

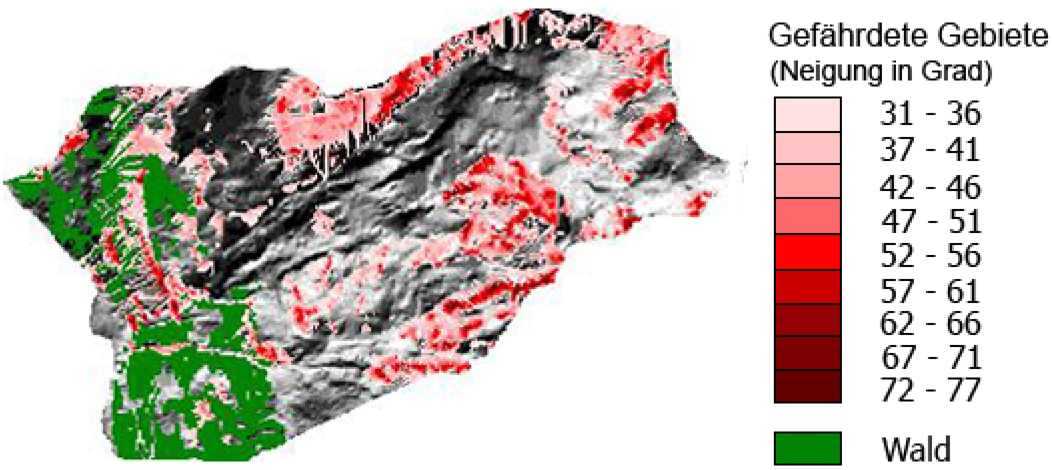
Derivatives	Output type	Description
Slope	Number	Slope at a point
Gradient	Number	Gradient between two points
Aspect	Number	Orientation of the slope

Curvature	Number	Curvature in a certain direction (for example plan and profile curvature)
Intervisibility	Yes/no	specifies whether the viewer can see a certain point
Viewshed	Polygon	Area which is visible from one or more points
Hillshade	Image	Shaded relief under a given illumination angle
Stream networks	Line	Lines of water runoff in the terrain
Catchment	Polygon	Area where other areas drain in
Profile	Line	Change in elevation of a surface along a line
Volume	Number	Calculation of volume change between two surfaces
Perspective image	Image	Perspective relief representation
Line of greatest slope	Line	Path along the steepest slope

Complex situations can be modeled in a GIS using terrain models. In the following section you will learn how to calculate an area which is threatened by rock fall. The input data are the following:

- Digitalized rocky areas (polygons)
- Digitalized forest cover (polygons)
- Digital terrain model

The modeling of a rock fall is performed as follows: The digitalized rocky areas are potential release areas. The line of greatest slope is calculated for each pixel within a rock area. The falling rocks are supposed to fall along the line of greatest slope. The simulated rock fall stops when the slope becomes less than 31° (this criterion was determined empirically in engineering experiments). In forest areas, the rocks stop faster (trees act as obstacles); there, the threshold value for the slope can be increased to 33. The image bellow shows the result of such analysis in the surroundings of Saas Baalen. The red colored area represents the area which could be affected by rock fall. The hue represents the slope.



Steinschlaggefahr in der Gemeinde Saas Baalen

The following matrix shows how application areas and terrain information can be matched. By clicking on the cells, you can choose which information is important for which application (by repeated clicking, the symbol size changes according to the legend). By clicking the button "check", you can compare your result to the proposed answers elaborated by (1991). You don't have to fill in the entire table to check your solution. Also note that Weibel's and Heller's solution is just one option. Your evaluation can be different. It is essential to think about why certain derivative information should be considered to be more important than other information.

Only pictures can be viewed in this version! For Flash, animations, movies etc. see online version. Only screenshots of animations will be displayed. [link]

Enlarge

1.1.2. Exercise

You are asked to model the spatial distribution of potential solar radiation in Switzerland using a GIS. Discuss with your colleagues which information is needed. Use the discussion forum.

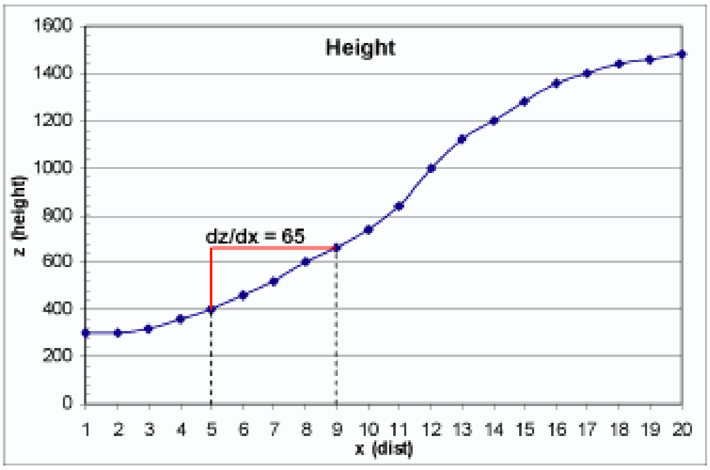
1.2. Geomorphometry

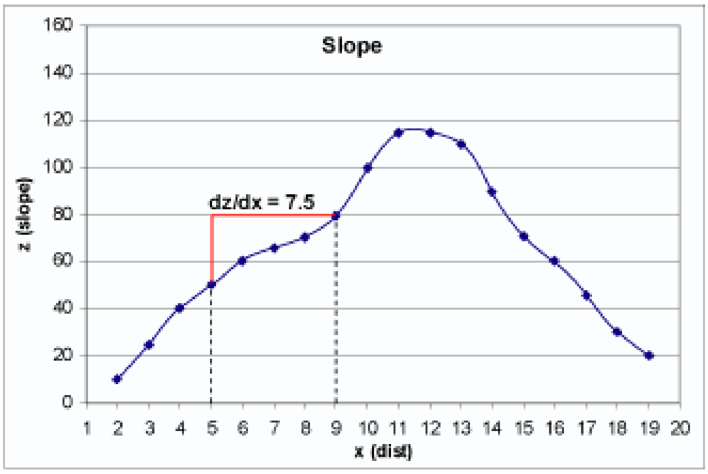
Geomorphometry deals with quantitative land surface observation and analysis. Therefore, different information such as slope, aspect and slope are extracted from digital terrain models. These parameters are used in various applications; e.g. aspect is used in vegetation geography, or altitude, aspect and gradient are parameters which are used for the modeling of potential alpine permafrost. Slope and aspect are required again for the modeling of potential avalanches. This unit is dedicated to the definition of this information. Furthermore, the fundamental techniques used to derive parameters such as gradient, aspect and curvature from digital terrain models, are presented.

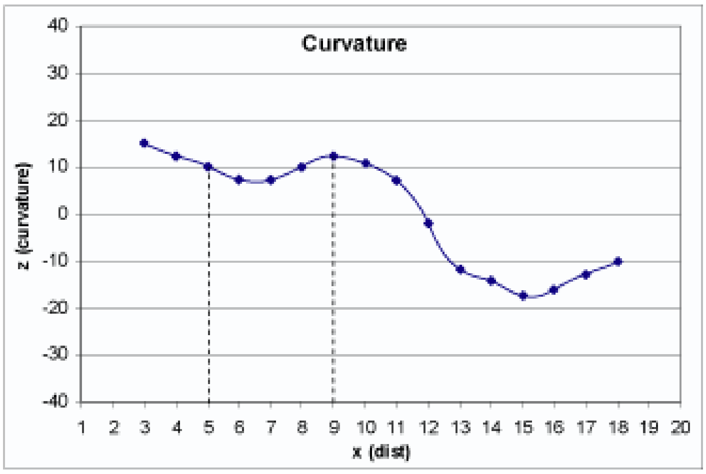
1.2.1. Slope

The slope at a point is given by the tangent plane. In order to calculate the slope, the derivatives of the surface in the direction of the x- and y-coordinate have to be known.
Therefore, special methods are needed to estimate the derivatives from elevation models. The most common method in grid based terrain models is called "finite difference" (Horn 1981).
To explain the principle of finite difference, we will first think about the one-dimensional case (not a surface). The following figure shows how the first derivative (slope) can be formed by calculating the difference quotient from the altitude (dz) and the distance (dx). Based on the first derivative, the second derivative can be calculated, which is the curvature. In the illustrated example below, the increment is equal to 4. This means that, starting at the central point, the finite difference is calculated for the two neighboring points on the left and the two neighboring points on the right. The derivative is assigned to the central point. In the illustration, the central point and the other four points taken into account are marked in red.

x	height	slope	curvature
1	300		
2	300	10	
3	320	25	15
4	360	40	12.5
5	400	50	10
6	460	60	7.5
7	520	65	7.5
8	600	70	10
9	660	80	12.5
10	740	100	11.25
11	840	115	7.5
12	1000	115	-2.5
13	1120	110	-11.25
14	1200	90	-13.75
15	1280	70	-16.25
16	1360	60	-15
17	1400	45	-12.5
18	1440	30	-10
19	1460	20	
20	1480		







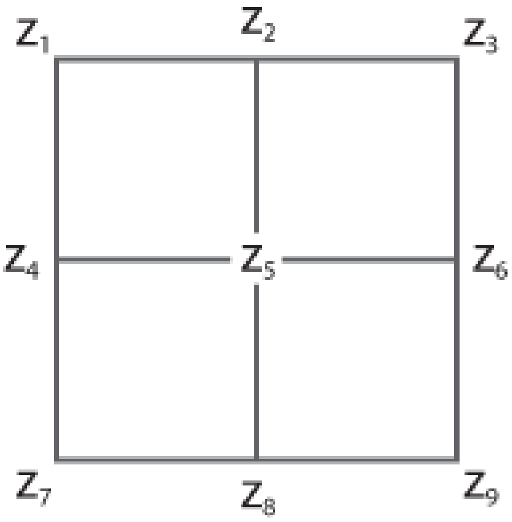
In the two-dimensional case, there is the formula given by (Horn 1981) to estimate the slope, using finite differences:

$$Slope = arctan\sqrt{\left(\frac{dz}{dx}\right)^2 + \left(\frac{dz}{dy}\right)^2}$$

with

$$\frac{dz}{dx} = \frac{(z_3 - z_1) + 2\,(z_6 - z_4) + (z_9 - z_7)}{8\Delta x}$$
$$\frac{dz}{dy} = \frac{(z_9 - z_3) + 2\,(z_8 - z_2) + (z_7 - z_1)}{8\Delta y}$$

The numbering of the points in the 3-by-3 neighborhood around the central point (z5) is shown in the illustration below. The differences that go through the central point, z5, are doubled (see also the formula stated above).



There are also methods to derive directional information from a terrain model based on linear interpolated TINs. The altitude in a triangle can be calculated using the equation of the plane `z = ax + by + c` , where x, y, and z are the coordinates of the point for which the altitude has to be calculated. A, b and c are calculated using the three vertices of the triangle. Like this, the derivatives in direction x (a) and in direction y (b) are found.

1.2.2. Aspect

Aspect is the direction (clockwise from North = azimuth) to which the steepest slope of the plane tangent faces. To calculate the aspect, the derivative in direction x and in direction y have to be calculated (Horn 1981):

$$Aspect = arctan\left(\frac{b}{a}\right)$$

with

$$a = \left(\frac{dz}{dx}\right)$$

$$b = \left(\frac{dz}{dy}\right)$$

In addition, you need to take into account whether the values are negative, positive or zero ("mod" stands for modulo division known as the remainder):

$$Aspect = \begin{cases} arctan\,\frac{b}{a}\; mod\, 360, & \frac{dz}{dx} \in \mathbb{R}, \quad \frac{dz}{dy} < 0 \\ arctan\,\frac{b}{a} + 180, & \frac{dz}{dx} \in \mathbb{R}, \quad \frac{dz}{dy} > 0 \\ 90, & \frac{dz}{dx} < 0, \quad \frac{dz}{dy} = 0 \\ 270, & \frac{dz}{dx} > 0, \quad \frac{dz}{dy} = 0 \\ nicht\; definiert, & \frac{dz}{dx} = 0, \quad \frac{dz}{dy} = 0 \end{cases}$$

1.2.3. Curvature

The second order derivative from digital terrain models is the curvature, which includes the plan and profile curvatures. The profile curvature is parallel to the direction of the maximum slope and the plan curvature is perpendicular to the direction of maximum slope. A negative value indicates a convex form; a positive value indicates a concave form. (1987) give the most common calculation method for raster models. A local 4th order polynomial with 9 parameters is fitted through all the nine points in the 3-by-3 neighborhood, as shown in the following illustration (including the numbering of the points in the formula). The plan curvature and the profile curvature can be calculated for the central point z_5 using the following formula:

$$Z = f(x,y) = Ax^2y^2 + Bx^2y + Cxy^2 + Dx^2 + Ey^2 + Fxy + Gx + Hy + I$$

mit

$$A = \frac{\frac{z_1+z_3+z_7+z_9}{4} - \frac{z_2+z_4+z_6+z_8}{2} + z_5}{L^4}$$

$$B = \frac{\frac{z_1+z_3+z_7+z_9}{4} + \frac{z_2-z_8}{2}}{L^3}$$

$$C = \frac{\frac{z_1+z_3+z_7+z_9}{4} + \frac{z_4-z_6}{2}}{L^3}$$

$$D = \frac{\frac{z_4+z_6}{2} - z_5}{L^2}$$

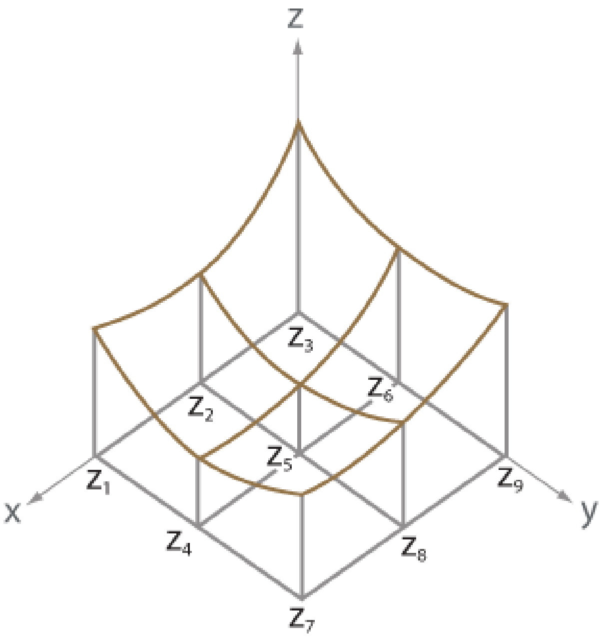
$$E = \frac{\frac{z_2+z_8}{2} - z_5}{L^2}$$

$$F = \frac{-z_1 + z_3 + z_7 - z_9}{4L^2}$$

$$G = \frac{-z_4 + z_6}{2L}$$

$$H = \frac{z_2 - z_8}{2L}$$

$$I = z_5$$



$$L = \text{Maschenweite des Quadratgitters [m]}$$

$$\text{Slope} = -(G^2 + H^2)^{1/2}$$

$$\text{Aspect} = arctan\left(\frac{-H}{-G}\right)$$

$$\text{Profile Curvature} = \frac{-2(DG^2 + EH^2 + FGH)}{G^2 + H^2}$$

$$\text{Planform Curvature} = \frac{2(DH^2 + EG^2 + FGH)}{G^2 + H^2}$$

In the following illustration there are colored 3D visualizations of a terrain. Which of the derivatives is colored?

Only pictures can be viewed in this version! For Flash, animations, movies etc. see online version. Only screenshots of animations will be displayed. [link]

1.2.4. Discussion

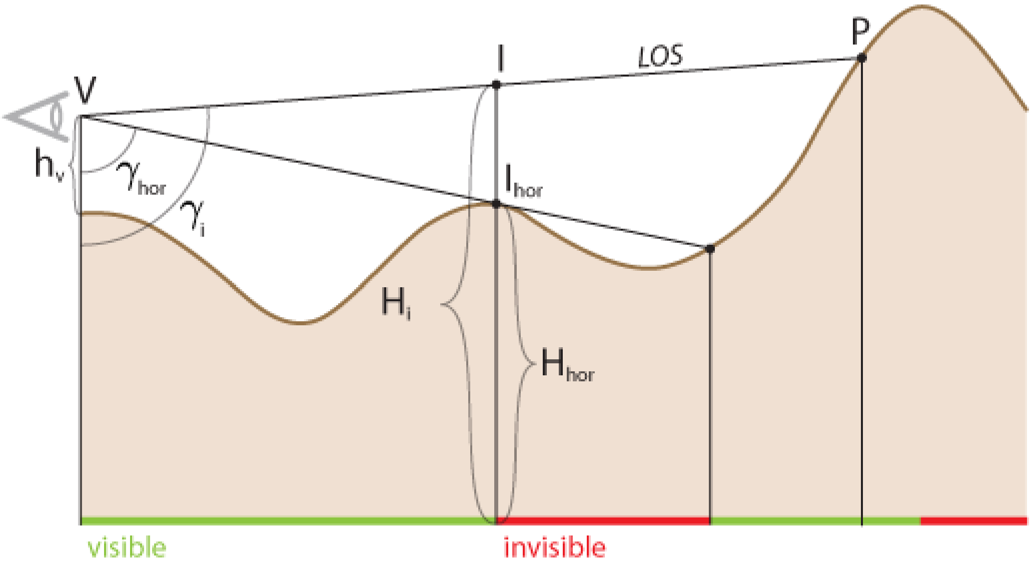
In this unit you learned how to derive information from a regular grid. Discuss the advantages and disadvantages of each presented method with your colleagues. Use the discussion forum.

1.3. Visibility analysis

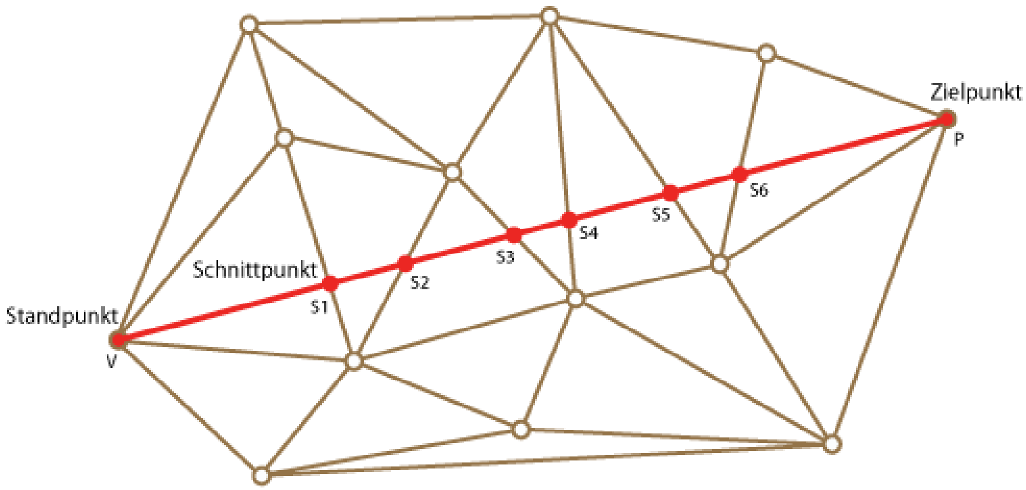
Digital terrain models can be used for many engineering and planning applications. In this unit, visibility analysis is discussed in detail. A visibility analysis detects all points that are visible from a given point based on a digital terrain model. The principle of this method is first demonstrated in 1D case and then discussed in a 2D scenario.

1.3.1. Calculation of visibility

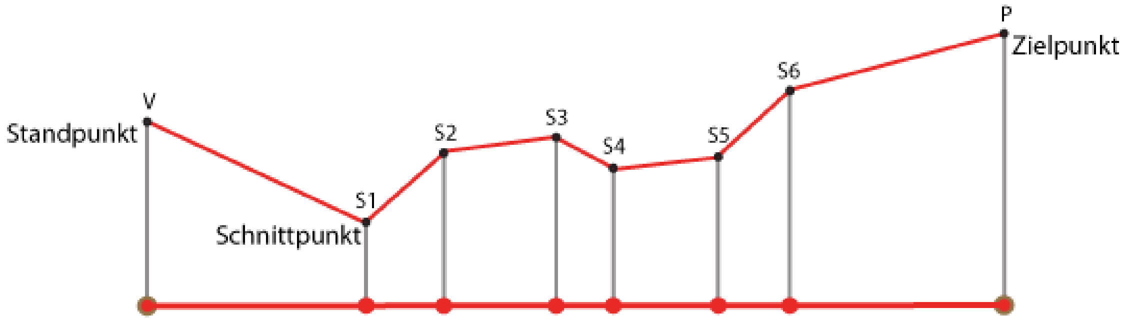
In the case of a 1D profile, we will investigate whether the target point *P* is visible from point *V*. In order to determine if there is visibility between point *P* and point *V*, a line of sight is calculated between the two. If there is a higher point lying on the line of sight, the target point is not visible. Otherwise, the target point is visible. The easiest way to perform such a test is to calculate the slope of the line of sight (*LOS*) between point *V* and point *P* and to compare it to the slope of the line of sight between point *V* and point I_{hor}, lying in between point *V* and point *P*. In other words: The vertical angles of the two lines can be compared. In the case that the angle of the *LOS* between *V* and *P* is bigger than the angle of the *LOS* between *V* and # $_{hor}$, *P* is visible. In the other case, *P* is not visible.

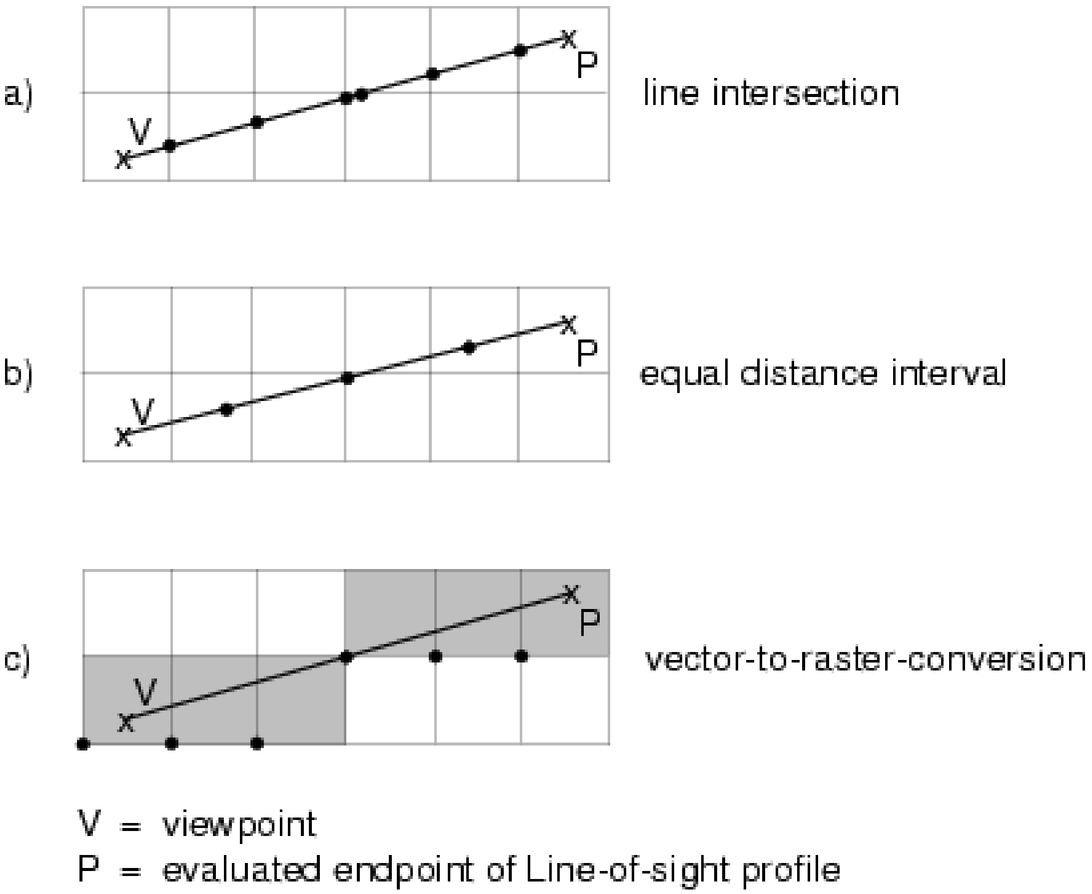


In a terrain model based on TINs, the altitude of the intersection points between the connection line V-P and the triangles have to be calculated first. The altitude at the intersection points S_1 to S_n can be calculated from the two corresponding vertices of the triangle by performing a linear interpolation. The result is a profile as shown in the figure below (1D case). At this point, the algorithm discussed above can be applied to calculate the LOS on the established profile.



Determination of the profile between the observation point V and the target point P in a grid based digital terrain model (raster): The profile is constructed on the intersection points between the connecting line of point V and point P and the edges of the grid (see figure a). Since the calculation of the intersections can be very computationally intensive, approximation algorithms are used to compute a profile. Have a look at the following figure: There are two possible approximation algorithms shown. In figure b, the altitude is retrieved in regular steps along the LOS. The corresponding altitudes of the cells, in which the points are lying, are assigned to the points. The second algorithm introduced in this chapter is illustrated in figure c: The LOS is converted into a raster and then compared to the digital terrain model.





Visibility analyses are applied in different fields. For example, it can be used to determine the location of an observation tower. By using a digital terrain model, different possible locations can be examined in a short period of time. The calculation can also be performed for different tower heights (variation of h_v). Another example is the use of visibility analysis for the calculation of the expansion of electromagnetic radiation (e.g. for the planning of mobile phone antennas). But in this case, the user should be aware that the area in which electromagnetic radiation can be received does not completely match with the visible area. This problem can be solved in GIS by situating the point a certain amount below the LOS so it does not to receive a signal. The amount of this reduction depends on the wavelength. This last example concerns wildlife biology: A GIS can be used to find the optimal area for the relocation of animals. The Rocky Mountain Bighorn Sheep for instance prefers areas that are visible from just a few locations. This reduces the possibility of being discovered by a predator.

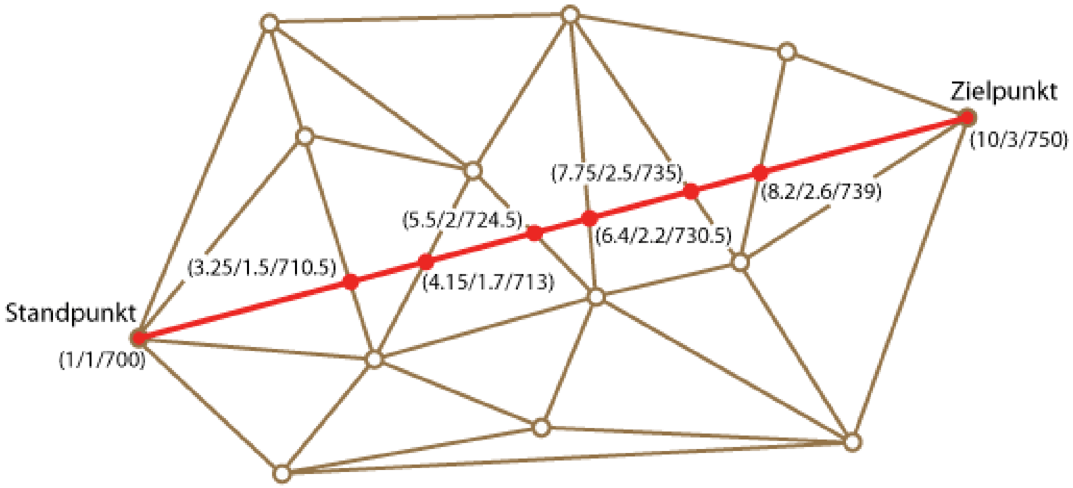
The map below shows the surroundings of Türlersee near Zürich (Switzerland). If you click on the topographic map, you can see which points are visible from the observation point (red point). After placing some points, a button appears named "showing the map". Click on it and the entire viewshed map will be visible. Is the village of Aeugst visible from the observation point?

Only pictures can be viewed in this version! For Flash, animations, movies etc. see online version. Only screenshots of animations will be displayed. [link]

To calculate the propagation of electromagnetic radiation, visibility analyses are slightly modified, as already mentioned. This method is used by mobile phone providers to map the areas where telephone reception is available. Have a look on the webpage of the telecommunications company **Orange**, to get an example for Switzerland. Look for other similar examples.

1.3.2. Self Assessment

In the following figure you can see a profile with altitudes and distances indicated. Calculate whether or not the target point is visible from the observation point. Use the calculator.

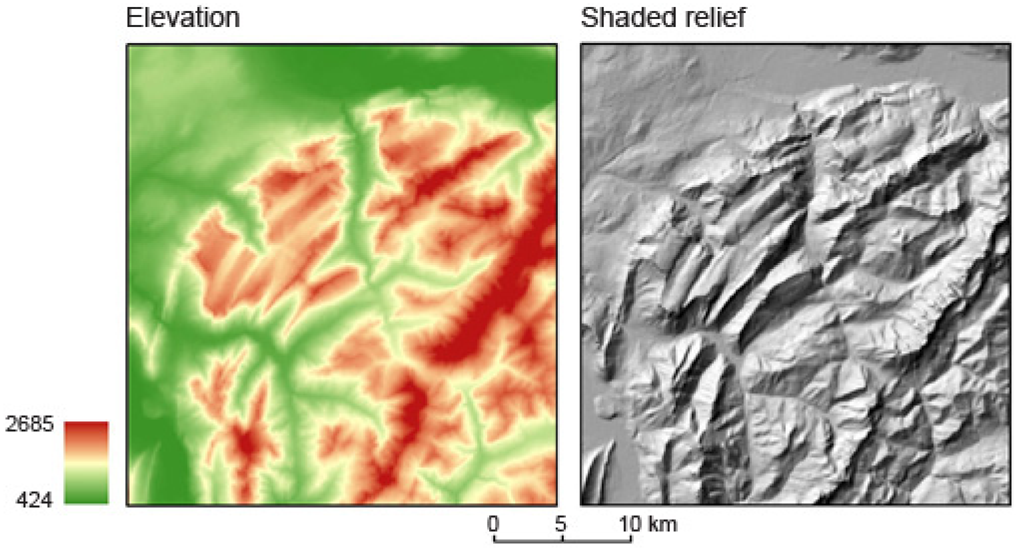


1.4. Hillshade

Sometimes, the relief in topographic maps is shaded to get a better impression of the third dimension. For such kinds of relief maps (hillshade), the illumination source is defined generally at an angle of 45° from the north-west. Even though this position is very unrealistic for the northern hemisphere, it is known that this sun position gives the best impression of relief in the third dimension. The brightness of the shadow of a given surface element (either a grid cell or a TIN section) depends on the following properties:

- Aspect and slope of the surface element
- Reflecting properties of the surface element

As an example have a look at the following illustration, where you can see the relief shading. The brightest areas are oriented in north-west direction, while the darkest areas are oriented in south-east direction (away from the sun).



Hypsographie (links), Reliefschattierung (rechts). Quelle: Shuttle Radar Topography Mission (SRTM)

1.4.1. Shading methods

Grid

(Horn 1981) proposes a method for relief shading of grid based maps (Burrough et al. 1998). In the first step the slope *p*, *q* has to be calculated for each grid cell in direction x (east-west) and in direction y (south-north):

$$p = \frac{dz}{dx}$$

$$q = \frac{dz}{dy}$$

In the second step the reflection can be approximated as follows:

$$R(p,q) = \frac{1}{2} + \frac{1}{2} * \frac{(p` + a)}{\sqrt{(b^2 + (p` + a)^2)}}$$

with:

$$p` = \frac{p_0 p + q_0 q}{\sqrt{(p_0^2 + q_0^2)}}$$

Where p' is the slope in the opposite direction to the illumination source. Let's set the illumination source on 45° north-west:

$$p_0 = \frac{1}{\sqrt{2}}$$

und

$$q_0 = -\frac{1}{\sqrt{2}}$$

The parameter a gives the possibility to choose the gray level for horizontal surfaces, b can be used to change the gray level with changing slope. It is recommended to set a=0 und

TIN

Relief shading of TIN based maps is performed similarly to the grid based method except that in this case, the reflection is not calculated for grid cells but for triangles.

1.5. Summary

Important information for many spatial models can be derived from digital terrain models using simple methods. Such methods are implemented in most commercial GIS software. They have been used for years in many different applications. In this lesson we have discussed some important information that can be derived from digital terrain models. Then we have discussed three important parameters of geomorphometry (slope, aspect, curvature) and explained how to calculate the visibility from an observation point. The methods presented are applicable for raster as well as for TIN data. A 3D impression of the terrain model can be calculated using the hillshade. Thereby, the reflection is calculated for each triangle (TIN) or grid cell (raster) on the basis of the slope and the position of the illumination source (45° NW).

1.6. Recommended Reading

- **Burrough, P. A.; McDonnell, R. A.**, 1998. *Principles of Geographical Information Systems*. New York: Oxford University Press.
- **Weibel, R.; Heller, M.**, 1991. Digital terrain modelling. *In:* **Maguire, D. J.; Goodchild, M. F.; Rhind, D. W.**, ed. *Geographic Information Systems - Vol. 1: Principles*. Harlow Longman.
- **Wilson, J.; Gallant, J.**, 2000. *Terrain Analysis. Principles and Applications*. New York: John Wiley and Sons.

1.7. Bibliography

- **Bernhard, L.; Weibel, R.**, 1999. Modelling snowmelt using a digital terrain model and GIS-based techniques. *In:* **Dikau, R., Saurer, H.**, ed. *GIS for Earth Surface Systems*. Stuttgart: Gebrüder Borntraeger, 25-46.
- **Burrough, P. A.; McDonnell, R. A.**, 1998. *Principles of Geographical Information Systems*. New York: Oxford University Press.
- **Fisher, P.**, 1996. Reconsideration of the Viewshed Function in Terrain Modelling. *Geographical Systems*, vol. 3, no.1, 33-58.
- **Horn, B.**, 1981. Hill shading and the reflectance map. *In: Proceedings of the IEEE, vol. 69*. p. 14-47.
- **Hugentobler, M.**, 2000. Fortpflanzung von Unsicherheiten in dreiecksbasierten digitalen Geländemodellen mit Intervallarithmetik. *Geoprocessing Series*, 38, 55 pp., Zürich: Geographisches Institut der Universität Zürich.
  Download: http://opac.nebis.ch/exlibris/aleph/u21_1/apache_media/D6Q2QFCK47VQRIKLEFUKJDVAXXGX5Q.pdf
- **Johnson, T.; Swift, D.**, 2000. A Test of a Habitat Evaluation Procedure for Rocky Mountain Bighorn Sheep. *Restoration Ecology*, vol. 8, no. 4S, p. 47-56.
- **Kidner, D. B.; Ware, J. M.; Sparkes, A. J.; Jones, C.B.**, 2000. Visibility Analysis with the Multiscale Implicit TIN. *Transactions in GIS*, vol. 4, no. 4, 379-408.
- **SRTM**. *Shuttle Radar Topography Mission* [online]. Available from: http://www2.jpl.nasa.gov/srtm/ [Accessed 2013-11-20].
- **Swisstopo**, 2000. Landeskarte der Schweiz - Blatt Albis 1111, 1:25000. Bern: Swisstopo. [Reproduziert mit Bewilligung von swisstopo (BA057224)]
- **Utelli, H.**, 1999. Die Möglichkeiten von GIS bei der Beurteilung der Steinschlaggefahr im alpinen Bereich. *Bulletin für angewandte Geologie*, 4 (1), 3-17.
- **Weibel, R.; Heller, M.**, 1991. Digital terrain modelling. *In:* **Maguire, D. J.; Goodchild, M. F.; Rhind, D. W.**, ed. *Geographic Information Systems - Vol. 1: Principles*. Harlow Longman.
- **Wilson, J.; Gallant, J.**, 2000. *Terrain Analysis. Principles and Applications*. New York: John Wiley and Sons.
- **Wood, J.**. *LandSerf* [online]. Available from: http://www.landserf.org/ [Accessed 2013-11-20].
- **Zevenbergen, L.; Thorne, C.**, 1987. Quantitative analysis of land surface topography. *Earth Surface Processes and Landforms*, 12 (1), p. 47-56.