Valleys Deep and Mountains High

Purpose

With this activity, you will learn and simulate how altitudes and the height of the Earth's surface can be measured from space. Later, you will explore different techniques for creating maps from these data that visualise the altitudes measured in the previous exercise.

Questions

How would you measure distances and heights?

How do you measure the distance to thunderstorms?

Why does this work?

Can you also define distances based on the speed of light? What are the units of distance between stars?

The problem is that clouds can block light. Are there other kinds of light/electromagnetic waves that can be used instead?

How do radar stations work?

Can you imagine a technology that permits measuring the height of the Earth's surface at various points?

Activity 1: Painting by Numbers

Materials needed:

- Landscape model (hidden inside a box)
- Box
- Wooden skewer
- Rulers, tape measures
- Colour pencils

The box contains a landscape model you will have to reconstruct with a series of altitude measurements. The model is hidden inside the box so that you cannot see it. The lid of the box is covered with a grid of points through which the model will be probed.

Use the skewer as a probe. Insert it in each hole or through each grid position and slide it down gently until it hits solid material (Figure 1).

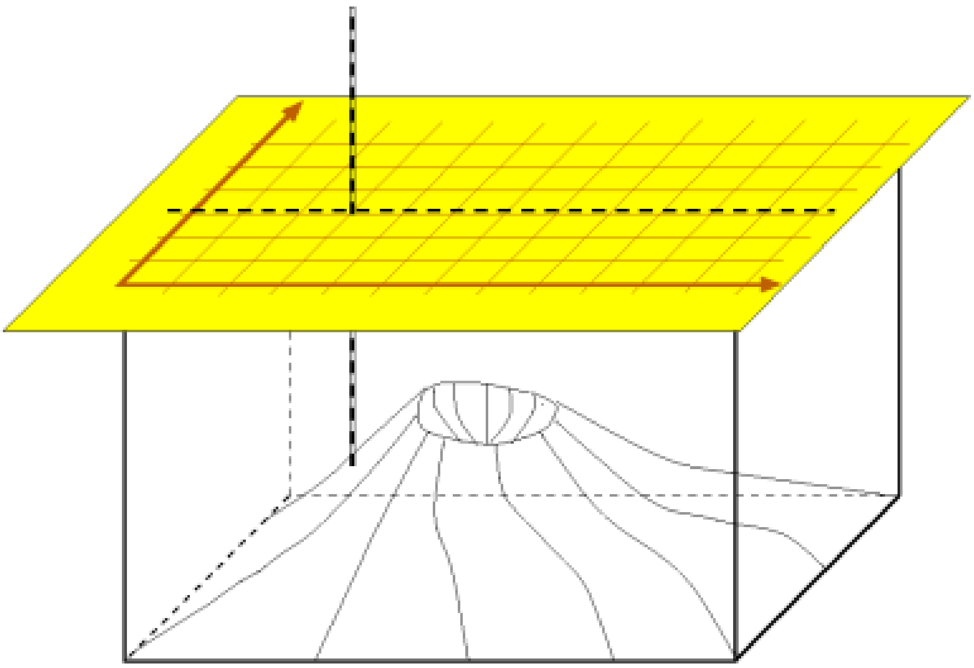

Figure 1: Schematic view of a landscape model inside a box with a measuring grid on top (Credit: O. Fischer, HdA).

Do not to use too much force.

It is important that the skewer remains perpendicular to the plane of the lid at all times.

Then measure the length of the protruding end and note down the value in the table cell that represents that position on the box (Table 1).

Make sure that you remember the orientation of the measuring grid so you can ensure its alignment with the data table.

A precision of 5 mm should be sufficient.

After covering all grid positions, you should have filled the table.

Table 1: Table of altitude measurements. Each cell corresponds to one grid point (Example).

	1	2	3	4	5	6	7	8	9	10	11	12
1												
2												
3												
4												
5												
6												
7												
8												
9												

What are the minimum and maximum values?

Where is the peak of the distribution?

Can you guess the shape of the hidden structure?

Now take a look at Figure 13. How are different heights represented in the map? Can you apply this method to your measurements?

Discuss what would be a reasonable number of steps to represent your data via a colour-coded map.

Usually, a colour table starting with violet for low numbers through different shades of blue, green, yellow, orange and red is suitable for assigning colours to number intervals (see Figure 18).

After agreeing on the number of colours, construct the colour-coded map by colouring the cells of the data table. See the example in the background information for instructions.

After the map is complete, discuss the probable shape of the model. What are the prominent features you can recognise?

To verify your conclusion, open the box. Does the structure within confirm your hypothesis?

Activity 2: Contour line map (optional)

Materials needed:

- Pencils
- Rulers
- Calculators
- Graph paper, millimetre paper, plotting paper (https://commons.wikimedia.org/wiki/File:Graph_paper_mm_A4.pdf)

Is the resolution of the map constructed during activity adequate to identify small-scale changes in the height of the landscape model?

Can you think of a way to infer the changes in altitude between the positions of the measuring grid?

Take a look at Figure 14. What do the contour lines represent?

How can you recognise a mountain peak?

How can you identify such lines of equal height considering the data you have previously gathered yourself? Have all the points of such a line been measured before?

In the following activity, you will produce a contour line map of the altitude measurements obtained during activity 1. Follow the instructions provided in the background information.

Begin with drawing a grid that coincides with the one on the box (Figure 19a-b). Use a pencil, a ruler and graph paper.

Remember that each grid point corresponds to a cell in Table 1.

Select a set of values that represents the measurements. Then begin with the highest numbers.

Use the equations in the corresponding section of the background information to interpolate between measured data and find their positions in the contour line map (Figure 19c).

For each chosen value, connect the derived points using a smooth line (Figure 19d).

The complete map should look similar to the example given in Figure 2.

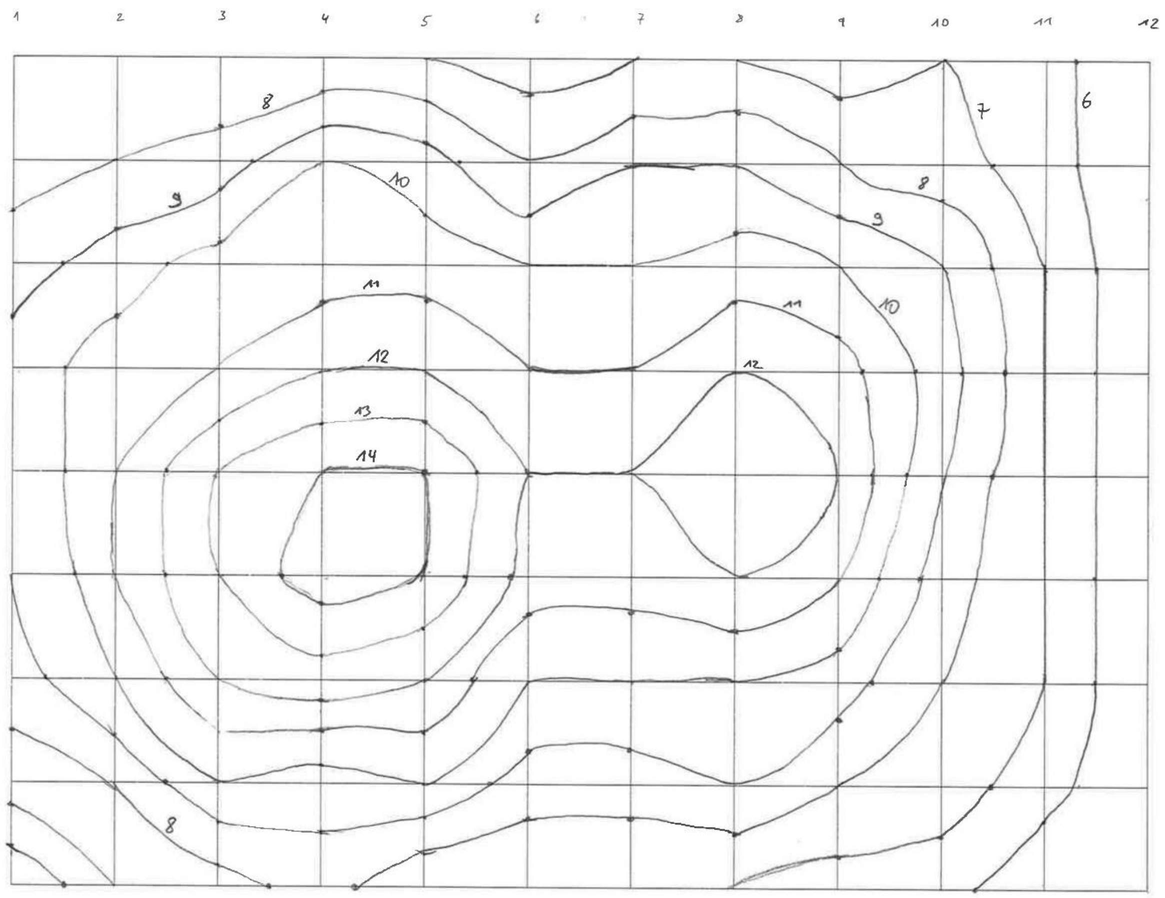

Figure 2: Example of a contour line altitude map (own work).

Activity 3: 3D surface map

Materials needed:

- Computer with Microsoft Excel installed (version 2010 or later)

Can you imagine what other tools can be employed to produce such maps? What do you think professional cartographers use? Do they still use a pencil and ruler for this?

For this activity, you will use Microsoft Excel to produce altitude maps from the measurements you have obtained during activity 1.

Enter your measurement data into an Excel table. The new table should look similar to Figure 3.

	A	B	C	D	E	F	G	H	I	J	K	L	M
1		Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Column 7	Column 8	Column 9	Column 10	Column 11	Column 12
2	Row 1	7	7	7	7	7	6.5	7	7	6.5	7	6.5	5
3	Row 2	7.5	8	8.5	10	9.5	8	9	9	8	7.5	6.5	5
4	Row 3	8.5	9.5	10.5	10.5	10.5	10	10	10.5	10	9	7	5
5	Row 4	9.5	10.5	11	12	12	11	11	12	11.5	9.5	7	5
6	Row 5	9	11	13	14	14	12	12	12.5	12	9	7	5
7	Row 6	8.5	11	13	14.5	14	11.5	11.5	12	11	8.5	7	5
8	Row 7	8.5	10	12	12.5	12	10	10	10	9.5	8	7	5
9	Row 8	7.5	8	10	9.5	10	8.5	8.5	9	8	7.5	6.5	5
10	Row 9	5	7	7.5	8.5	7	7	7	7	6.5	6.5	5	5

Figure 3: Excel table of altitude measurements (example only, own work).

You can produce a map of these data. Highlight the entries of the table including the row and column titles. Then select *Insert* → *Other charts* → *Surface* (first icon, Figure 4).

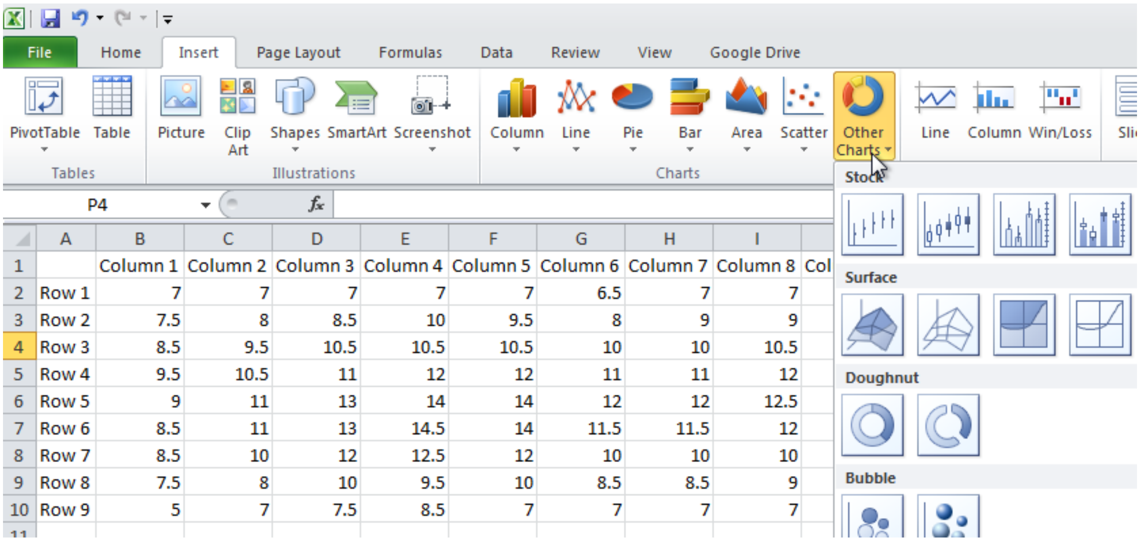

Figure 4: Menu item to produce a surface map of the data set (example only, own work).

A new window appears, containing a surface plot of the altitude measurements. This is already a good representation of the hidden landscape model. However, the scaling and the colour coding are initially arbitrary and need to be adjusted.

To modify the scaling, first click on the graph window to activate it. Then click on the tick values next to the vertical axis. A grey frame will appear. Then double-click, and a new window pops up (Figure 5). Change the options of 'Minimum', 'Maximum' and 'Major unit' from 'Auto' to 'Fixed'. Then enter the minimum and maximum integer values from the measurement. 'Major unit' indicates the step size for the scaling and the subsequent colour coding.

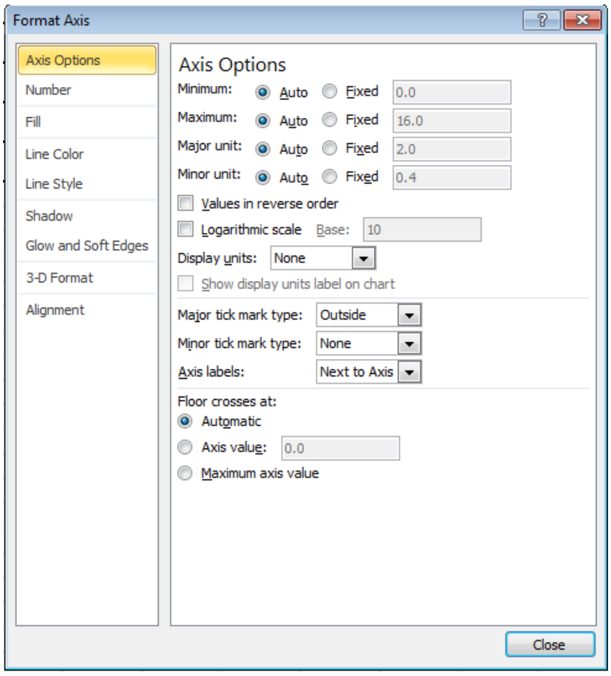

Figure 5: Axis options window of MS Excel.

To change the colour coding, click on the legend. Again, a grey frame appears. Then select the colour to be changed by clicking with the left mouse button. Then right-click and a small pop-up window appears that permits colour changes (Figure 6). Select the one that indicates 'Shape fill', i.e. the bucket. From the panel, any colour can be chosen. Do this for all entries of the legend.

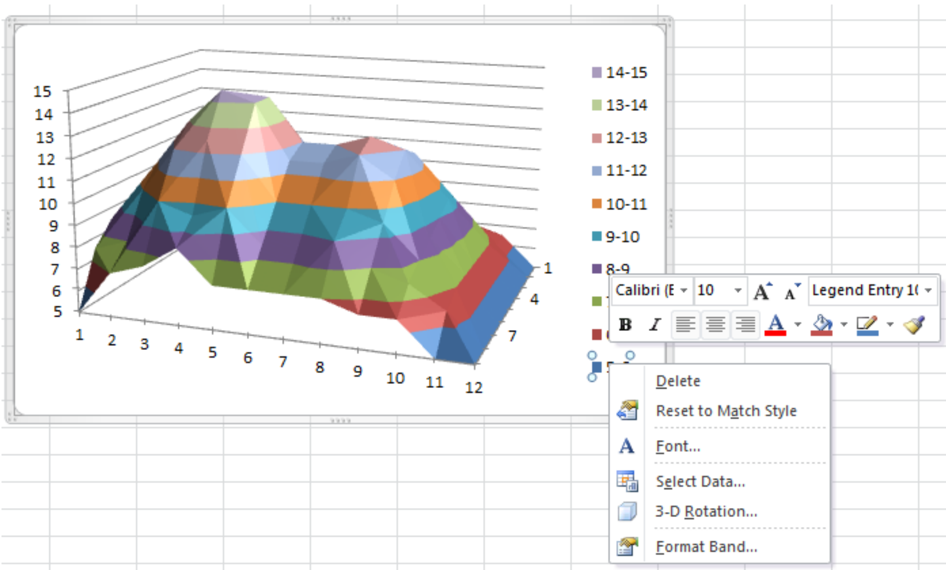

Figure 6: The colour coding can be adjusted via the legend.

Note that the order of the rows initially displayed in the plot is from bottom to top, which differs from the input table. The order can be changed by double-clicking on the row axis and selecting *Series in reverse order* in the new window (Figure 7).

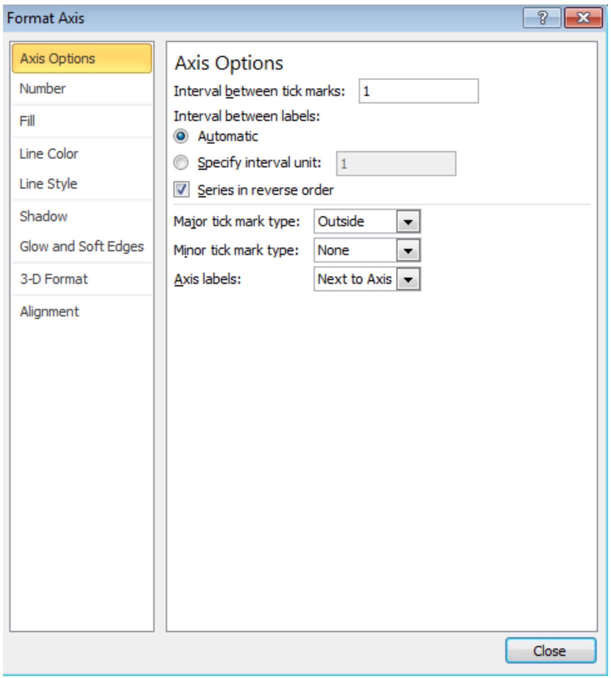

Figure 7: Dialogue window of MS Excel to change the settings of an axis. The axis representing the rows of the input table should be reversed.

Adjusting the viewing angles on the plot can be achieved by right-clicking on the plot and selecting *3-D Rotation*. The new window enables modification of the three angles of orientation (Figure 8).

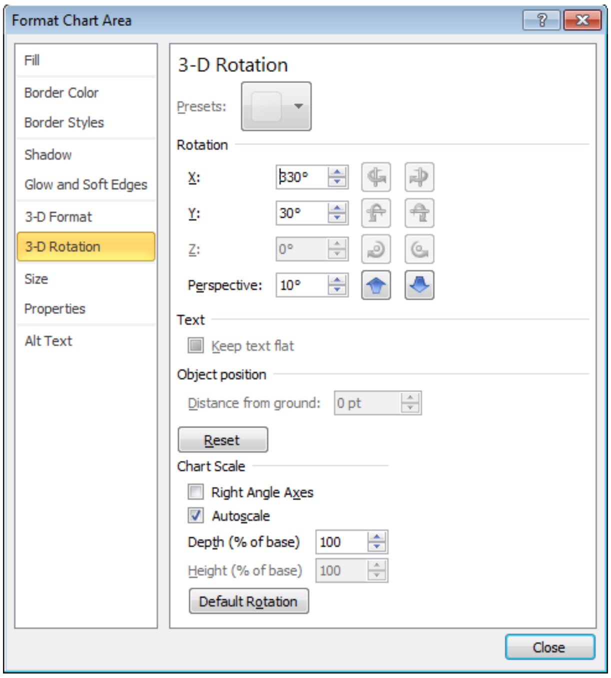

Figure 8: Options for rotating the surface map along three angles in space.

Produce two versions that show the data from different viewing angles. One should be right from the top and one should be from an angle that well represents the landscape model (see Figure 9 as an example).

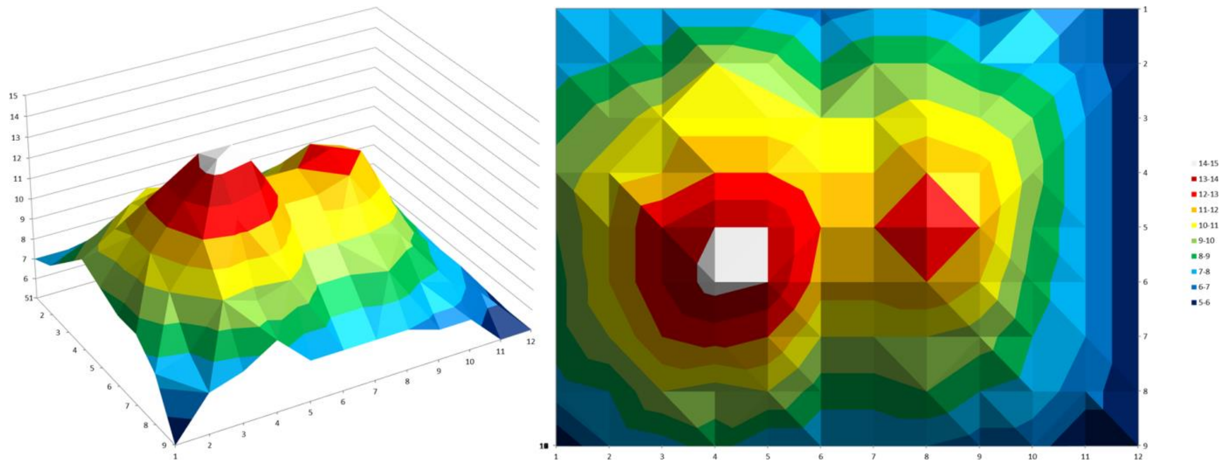

Figure 9: Surface plots of the altitude measurements used in the example.

Compare the results with the ones from the other activities.

Discuss the different techniques used to construct a map. How well is the real structure represented? Was the spatial sampling of the measurement sufficient?

Conclusion

Discuss the advantages and applications of satellite radar altimetry.

Map services like Google Earth have altitude information stored for each map position. How was that obtained?

Why have satellites been used for this? What is their advantage compared to on-ground measurements?

Can you imagine particular applications of radar altitude measurements taken from space?

Background information

Remote sensing

Besides classical in-situ methods like weather data analysis, field surveying or sample collection, satellite-based measurements are becoming an increasingly important source of data. Their advantage is the fast and complete coverage of large areas. However, satellite data are not always easy to interpret and need substantial analysis. In addition, they still need to be combined with direct measurements to correct for calibration artefacts.

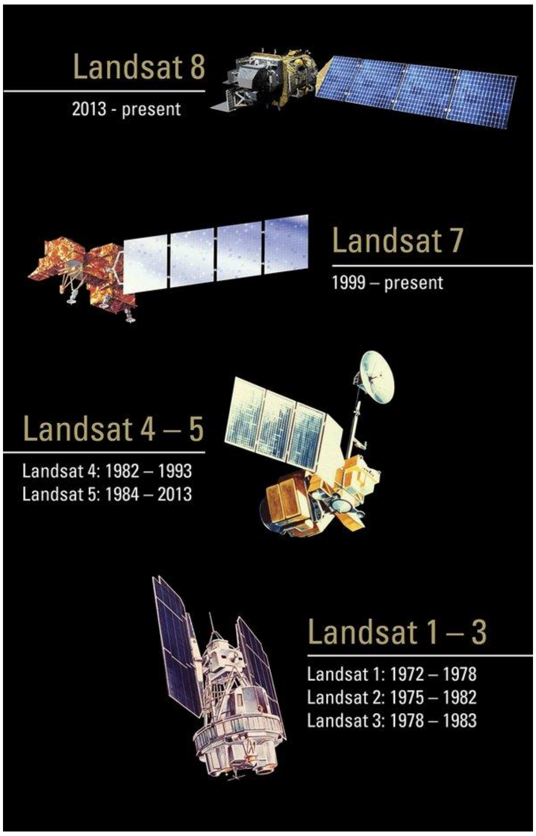

Figure 10: Overview of NASA Landsat remote sensing satellites (Credit: U.S. Geological Survey Department of the Interior/USGS).

The most abundant remote sensing devices are weather satellites. By employing suitable sensors, they provide information about cloud coverage, temperature distributions, wind speed and directions, water levels and snow thickness. Keeping the evolving climate change in mind, these data play an increasingly important role in disaster management during draughts and floods and for climate simulations, atmospheric gas content and vegetation monitoring. In addition, urban and landscape management benefit from satellite data.

The first weather satellites were launched by NASA as early as 1960. In the early 1970s, NASA started their earth observation programme using Landsat satellites (Figure 100). In Europe, France was the first, with their SPOT satellite fleet. This was followed by the remaining European countries in the 1990s after the foundation of ESA, the European Space Agency.

The Copernicus Programme

Since 1997, the USA and NASA have been developing a massive programme to explore the Earth, designated the *Earth Observation System*, which consists of a large number of different satellites. The European equivalent, the *Global Monitoring for Environment and Security* (GMES), has been under development since 1998. In 2012, the programme was renamed to *Copernicus*. Information products for six applications are being derived from the satellite data: ocean, land and atmosphere monitoring; emergency response; security and climate change. The data products are offered to the public free of charge. They are supplied via two branches: space-based remote sensing devices (satellite component) and airborne, ground and marine probing (in-situ component). The core of the satellite component is the fleet of Sentinel satellites built exclusively for the *Copernicus* projects. They are supplemented by other domestic and commercial partner missions. The first Sentinel satellite (Sentinel 1-A) was launched in 2014. Sentinel-2A and 3-A followed in 2015 and 2016, respectively.

Figure 11: Computer model of the Sentinel-1A satellite launched on 3 April 2014 (Credit: ESA/ATG medialab).

Radar altimetry

Radar altimetry is a procedure used to identify differences in altitude on different terrains. Radar (radio detection and ranging) is a standardised method for measuring the height of the Earth's surface. Satellites emit very short radio pulses (a few picoseconds, 1 ps = 10^{-12} s) with frequencies of several gigahertz which are reflected by the Earth and received in return. The duration of the signal turnaround (ranging) is a measure of the distance between the surface and the satellite. The signal itself also contains information about the composition of the ground that reflect the signals in different ways depending on the conditions.

Satellites that apply this kind of measuring technique include Envisat, Jason-1, CryoSat and Sentinel-3A. In contrast to satellites that acquire images at visual wavelengths, radar satellites are largely independent of weather conditions and daylight. Radio waves transmit through clouds and so can probe the Earth's surface even through thick cloud coverage. Since their wavelength is considerably higher than that of the visual range of the electromagnetic spectrum, the spatial resolution is worse. This disadvantage, however, can be overcome by special measuring and data analysis techniques. In addition, with advances in technology, each new generation of instruments has greater sensitivity and accuracy than the previous generation.

An important application of radar today is determining the varying thickness of ice on sea and land. This information provides clues about the worsening climate change and the amount of water originating from thawing ice. A satellite launched for exactly this purpose is the European CryoSat-2. The data obtained from radar altimetry using this satellite are used to produce topographical maps that provide altitude information.

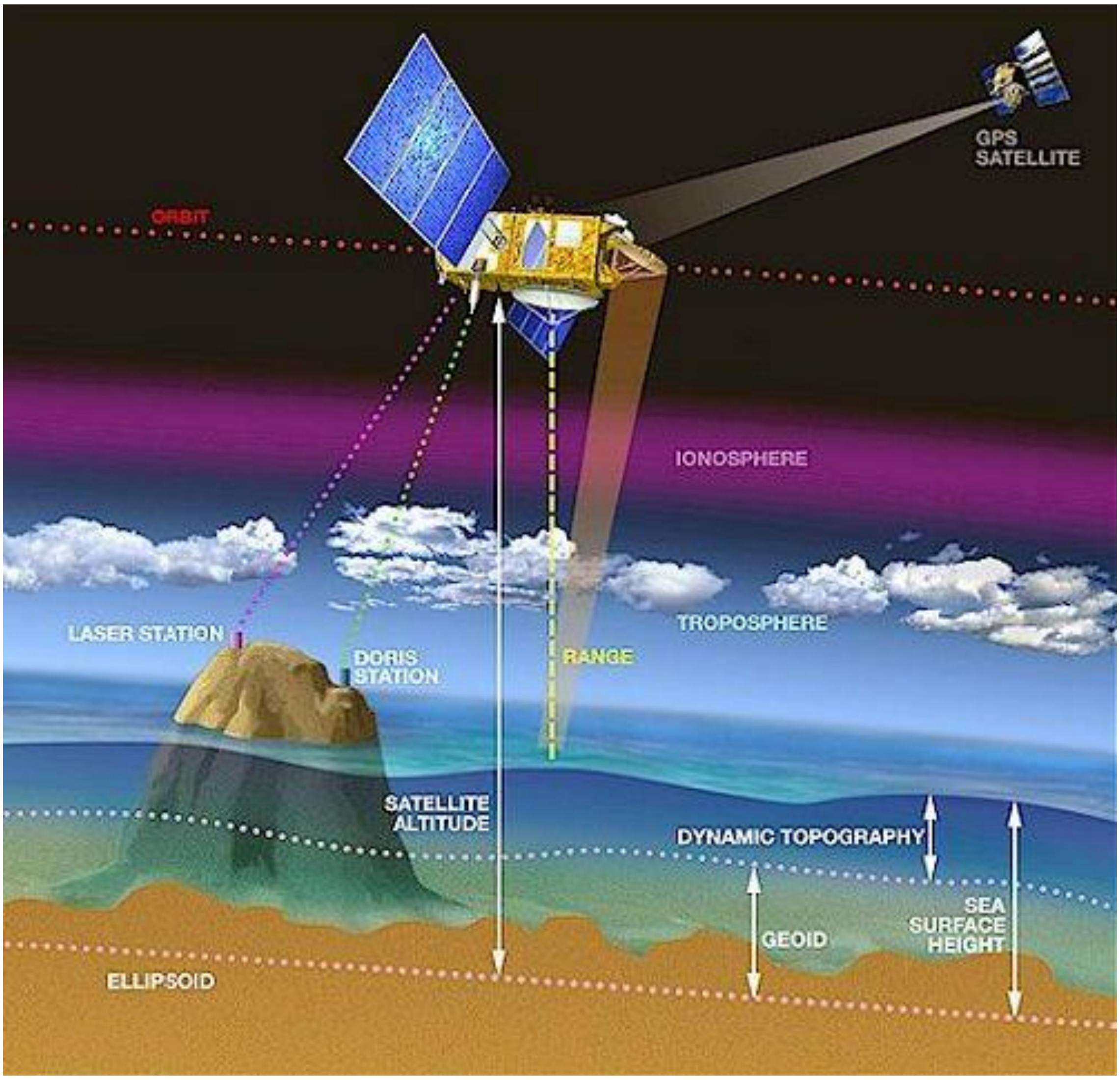

Figure 12: Illustration of the procedure of radar altimetry (Credit: ESA).

Colour-coded altitude map

Conventional maps are typically two-dimensional bird's eye views that provide constellations of landmarks and objects like roads, cities and borders. A simple method to indicate altitudes on maps is colour coding (Figure 1313). This is done by assigning colours to selected altitude ranges. This provides an overview of altitude distributions with the same spatial resolution as the measuring grid. An example how to produce such a map is given further below.

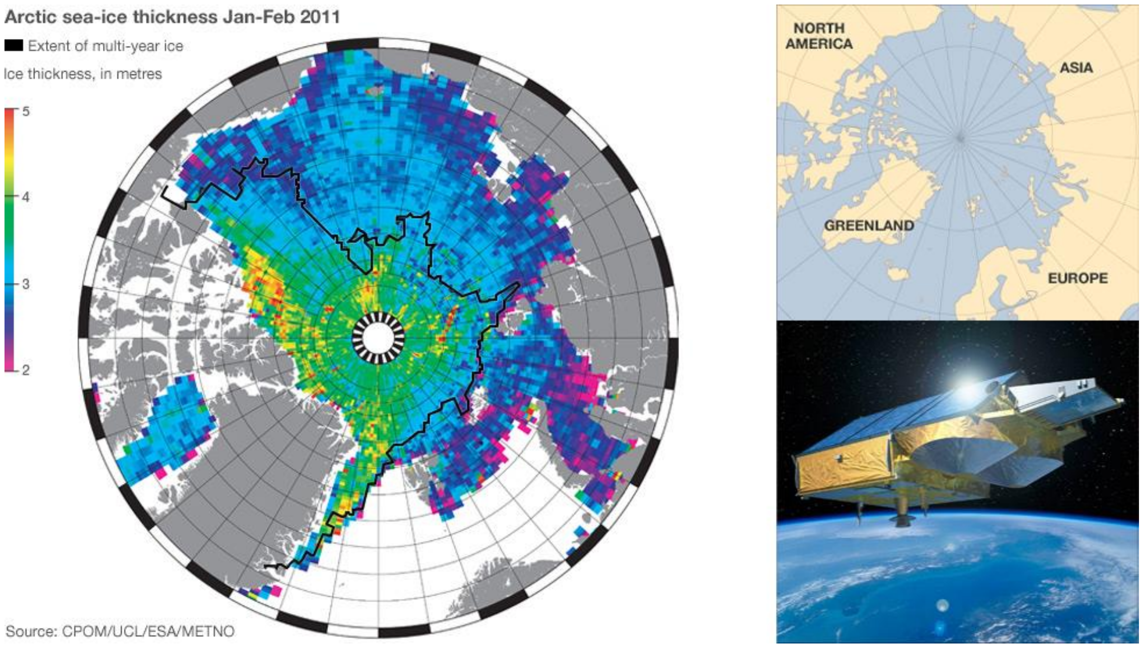

Figure 13: A colour-coded altitude map of the arctic ice cover based on measurements of the CryoSat-2 satellite (Credit: [BBC News, 21 June 2011](); [CPOM/UCL/ESA]()).

Contour lines

Particularly in topographical maps, altitudes are represented by contour lines that indicate zones of equal altitudes. An example is given in Figure 14, which provides both altitudes above and depths below sea level.

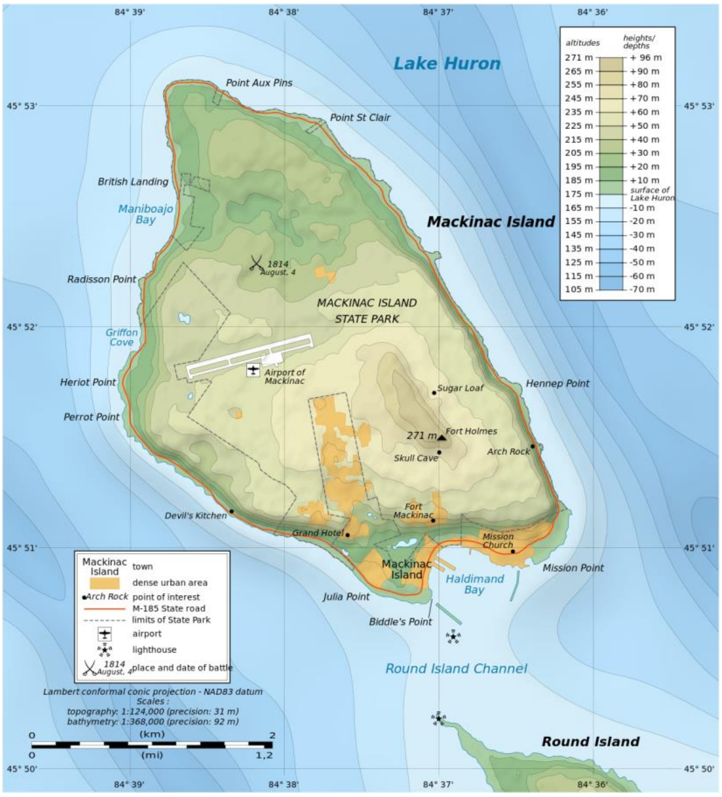

Figure 14: Example of a topographical map with contour lines (Credit: Eric Gaba ([Sting]() - [fr:Sting]()), https://commons.wikimedia.org/wiki/File:Mackinac_Island_topographic_map-en.svg, 'Mackinac Island topographic map-en', https://creativecommons.org/licenses/by-sa/3.0/legalcode).

One can imagine contour lines as intersections of horizontal cuts through the landscape at equidistant altitude steps.

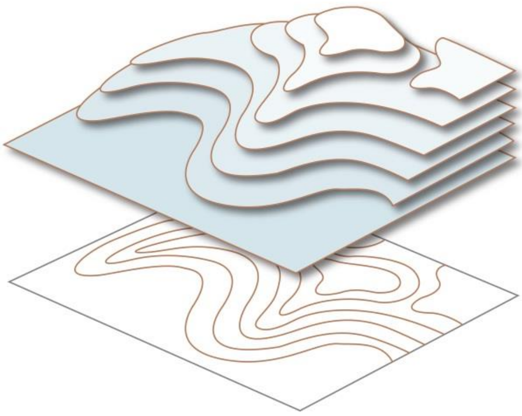

Figure 15: Illustration of the generation of contour lines indicating altitude. Contour lines can be regarded as the intersections of horizontal cuts through the landscape at equidistant altitude steps (Credit: Bavarian Surveying Administration).

The geometry of the contour lines allows one to derive the characteristics of the landscape from them. The closer the lines are aligned to each other, the steeper is the slope. Closed lines indicate a summit or a trough.

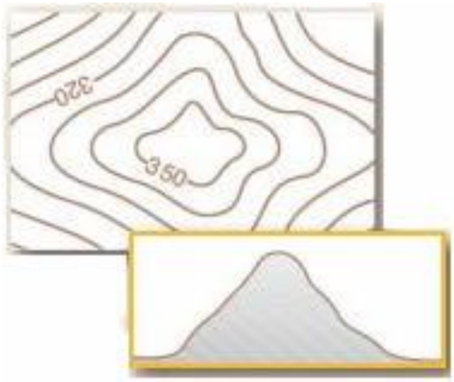

Figure 16: Closed lines with increasing altitude from the outside in indicate a summit (Credit: Bavarian Surveying Administration).

Constructing altitude maps

Altitude or topographic maps provide information on the geometry of landscapes in all three dimensions, provided the underlying grid of altitude measurements is sufficiently dense. In the example to be used in this section, we assume an area that was probed with an equidistant 4 × 4 grid. The results are given in 2. The numbers are without units because they are irrelevant for this example. In reality, they can be given in metres, kilometres or the signal travel time.

Table 2: Grid of simulated altitude measurements. The numbers represent altitudes in arbitrary units.

	Column 1	Column 2	Column 3	Column 4
Row 1	1	4	7	10
Row 2	2	5	8	11
Row 3	2	7	12	17
Row 4	3	6	12	24

Colour-coded map

The simplest way of producing a map from this is to construct a colour-coded altitude map as shown in Figure 17. The choice of colours can support data interpretation. In this example, a colour map from dark blue via green, yellow and orange up to red is chosen. This corresponds to the colours of a rainbow or the visual light spectrum.

1	4	7	10
2	5	8	11
2	7	12	17
3	6	12	24

Figure 17: Colour-coded altitude map based on the simulated altitude measurements. The distribution of colours corresponds to the coordinate grid of the measurement. The colours depict the intervals 0–3, 4–7, 8–11, 12–15, etc.

Computer-based map

A computer-generated profile of the measurements is shown in Figure 18. It can be reproduced using MS Excel 2010 with the data plotted as a surface chart. As expected, small numbers indicate low altitudes and large numbers correspond to high altitudes. Altitude ranges are also colour coded. The intersections between colours can be interpreted as altitude contour lines. The next paragraphs demonstrate how contour maps can be constructed manually.

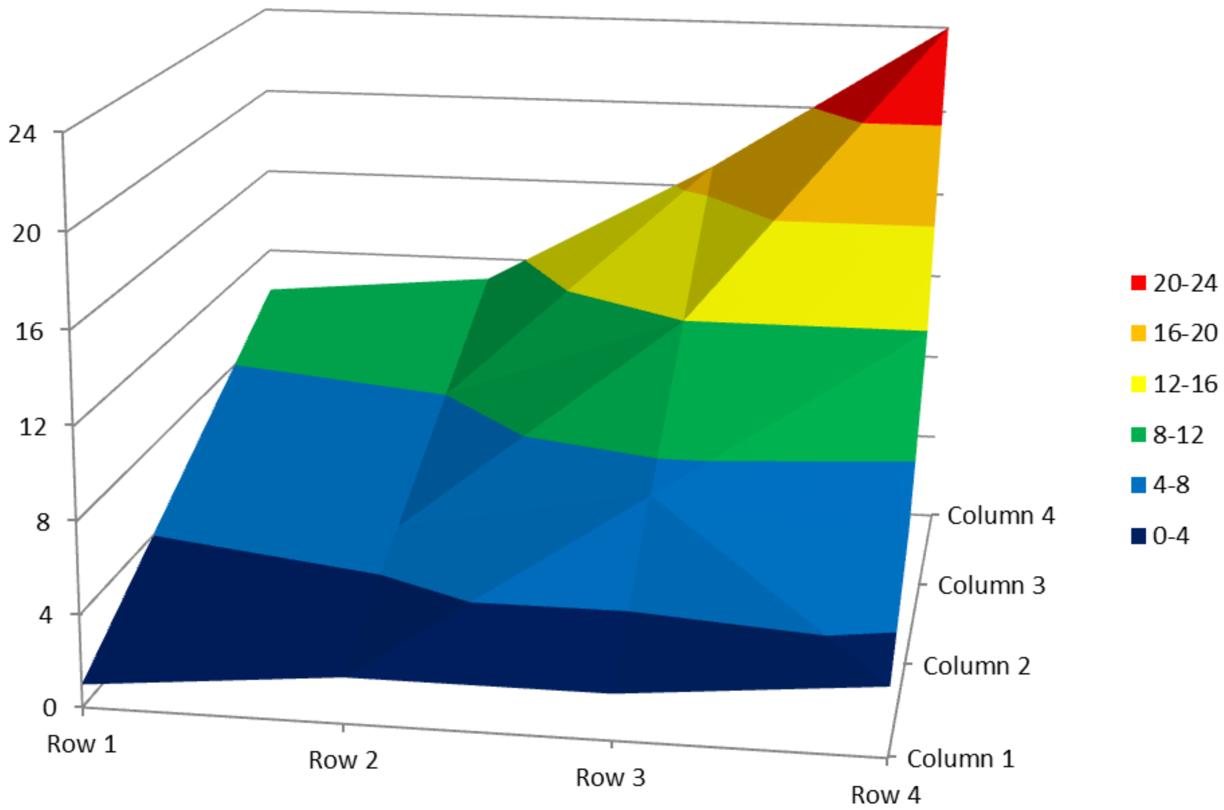

Figure 18: Profile of the simulated measurements. The altitude ranges are indicated as coloured zones. The intersections indicate contour lines.

Contour map

The individual steps are given in Figure 19. Sketch *a* represents the regular 4 × 4 measurement grid. The distances between the vertices define the scale of the map. The data obtained at those grid points are added in sketch *b* to help find the interpolated values in the next step. They should not be added to the real map.

A set of equidistant altitudes should be chosen for interpolation. In this example, we select 6, 9, 12, and 15. The corresponding values are found by linear interpolation – both horizontally and vertically. For instance, 6 must lie between 5 and 7. The proper positions are found by applying a linear equation between two neighbouring data points.

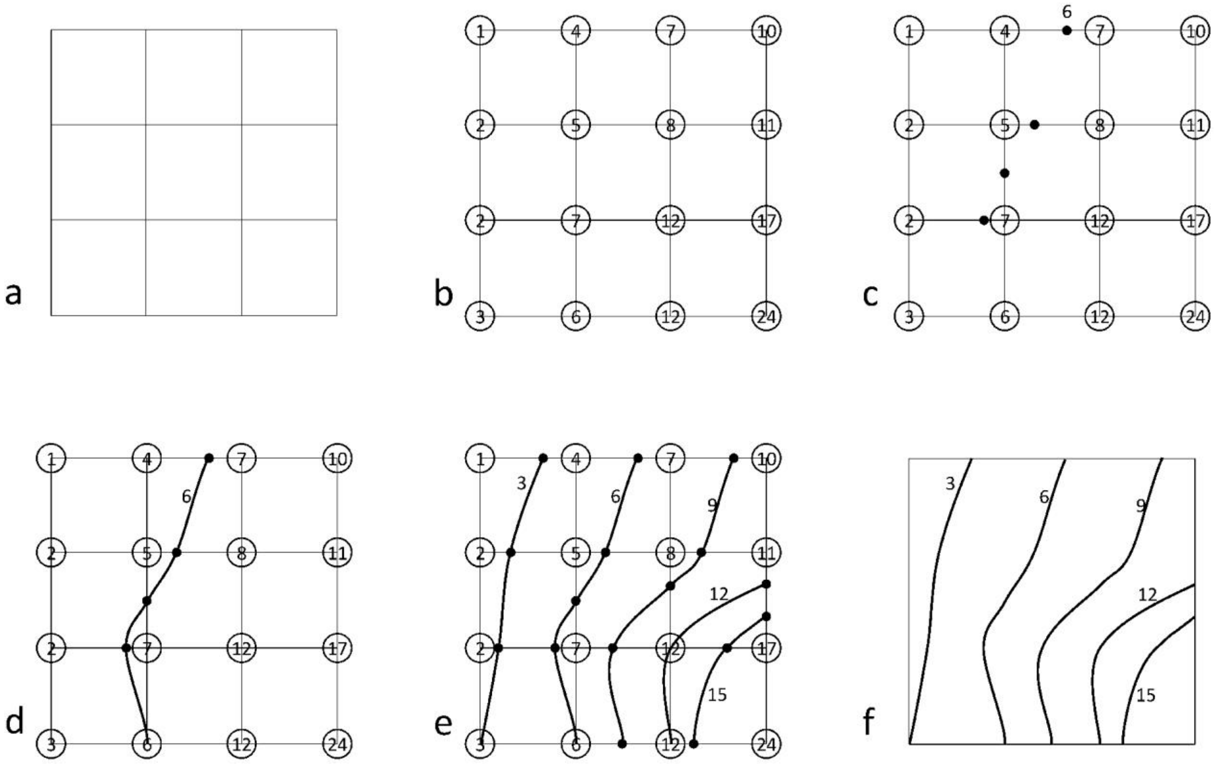

Figure 19: Construction of an altitude contour map. a) Regular 4 × 4 measurement grid; b) assignment of numbers to the 16 data points; c) horizontally and vertically interpolated data points for a given altitude; d) smooth connection of interpolated altitudes; e) interpolated contour lines of additional altitudes; f) resulting altitude contour map.

Imagine the distribution of altitude measurements shown in Figure 18 from a side perspective. Two neighbouring data points define a line (Figure 2020). Interpolating between individual values can then be done by applying linear equations. The measured values are assumed to be h_1 at position s_1 and h_2 at s_2. The slope of the connecting line is calculated as follows.

$$\frac{\Delta h}{\Delta s} = \frac{h_2 - h_1}{s_2 - s_1} = \frac{h_2 - h}{s_2 - s} = \frac{h - h_1}{s - s_1}$$

Position s of interpolated value h must lie between s_1 and s_2, which we assume to be separated by $\Delta s = 10$ units. This position can be determined by using the previous equation and deriving

$$s - s_1 = \frac{\Delta s}{\Delta h}(h - h_1) = \frac{s_2 - s_1}{h_2 - h_1}(h - h_1)$$

$$s_2 - s = \frac{\Delta s}{\Delta h}(h_2 - h) = \frac{s_2 - s_1}{h_2 - h_1}(h_2 - h)$$

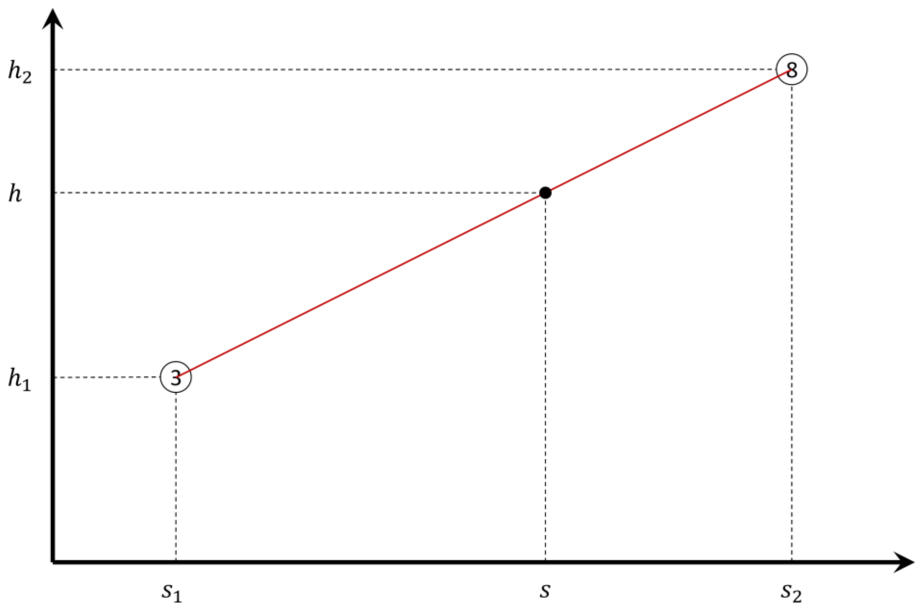

Figure 20: Visualisation of the linear interpolation between two data points.

In line with the example given in Figure 20, known variables have the following values:

$$\Delta s = 10$$

$$h_1 = 3$$

$$h_2 = 8$$

$$\Longrightarrow \Delta h = 5$$

$$\Longrightarrow \frac{\Delta s}{\Delta h} = 2$$

We want to construct the interpolated contour line for value 6. This means

$$h = 6$$

$$\Longrightarrow s - s_1 = \frac{\Delta s}{\Delta h}(h - h_1) = 2 \cdot (6 - 3) = 6$$

The interpolated data point that belongs to the contour line of value 6 can be found at a distance of 6 units from grid point s_1. This must be repeated for all neighbouring pairs of values. The result is given in Figure 19*c*. The resulting points are connected with a smooth line, which leads to sketch *d*.

Applying this procedure to all contour line values results in sketch *e*. The proper altitude contour map is given in sketch *f*.

In general, interpolating is not allowed between diagonally neighbouring grid points, because the interpolated lines usually do not lie within the plane of the square that is formed by four neighbouring grid points (Figure 21).

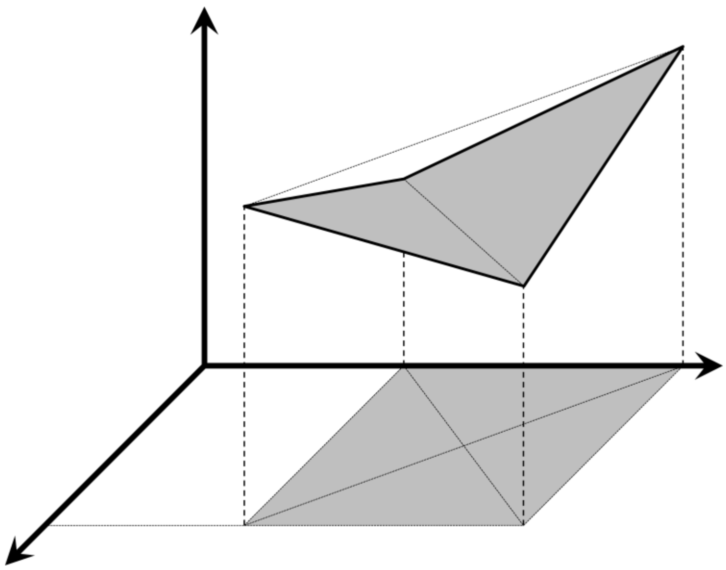

Figure 21: Diagonal lines of a measuring grid that consists of square cells (grey) are generally not in the plane of the square. Therefore, they must not be used for interpolating and constructing contour lines.