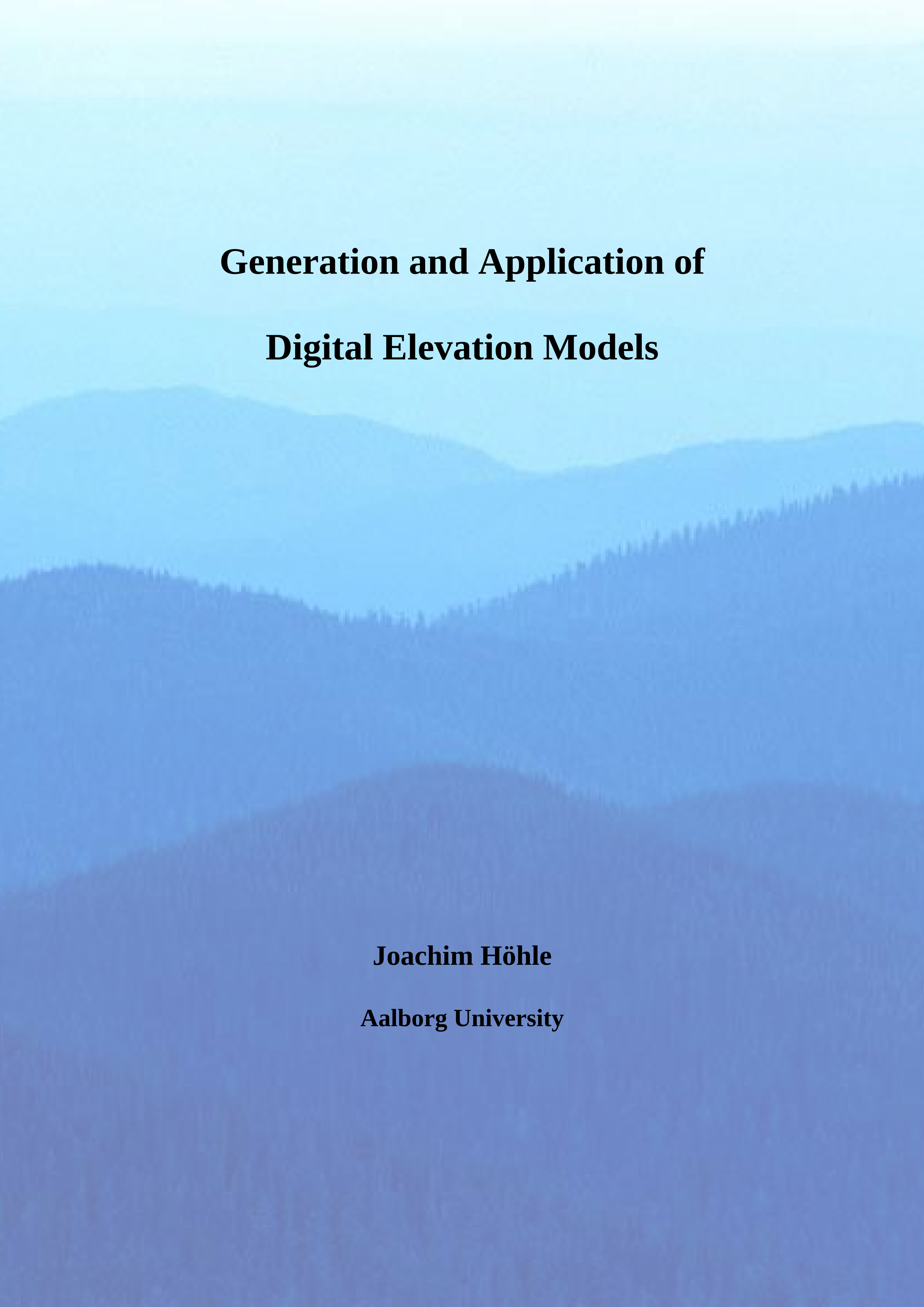

Generation and Application of Digital Elevation Models

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Denne afhandling er i forbindelse med de nedenfor anførte tidligere offentliggjorte afhandlinger af Akademisk Råd ved Det Teknisk-Naturvidenskabelige Fakultet ved Aalborg Universitet antaget til forsvar for doktorgraden i teknik.

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Dekan

Tidligere offentliggjorte afhandlinger:

1. Accuracy Assessment of Digital Elevation Models by Means of Robust Statistical Methods (together with M. Höhle)
2. DEM Generation Using a Digital Large Format Frame Camera
3. Photogrammetric Measurements in Oblique Aerial Images
4. The EuroSDR Project "Automated Checking and Improving of Digital Terrain Models"
5. Automated Quality Control for Orthoimages and DEMs (together with M. Potuckova)
6. The Automated Orientation of Aerial Images
7. On the Production of Photo-realistic and Dynamic 3D-Models of Building Structures by Means of Digital Photogrammetry
8. The Automatic Measurement of Targets
9. Experiences with the Production of Digital Orthophotos
10. Application of Terrain Modelling in Coastal Areas

Generation and Application of Digital Elevation Models

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1. Introduction

The world around us consists of differences in elevation and people have to cope with them. Water runs down from hills and mountains and finds its way from brooks to rivers which end in the sea. After heavy rainfall the water streams over its banks and floods the surroundings. Enormous damage may then occur and the live of people and animals may come in danger. In times of storms the sea level suddenly rises and flat coastal areas are flooded. Damages and death may happen then too. In order to prevent such catastrophes dikes and dams have to be built and people have to be warned or rescued in good time. Such scenarios can be simulated when the elevations in these areas are known.

Communication by means of cell phones requires antennae on towers and buildings. Their positioning in the landscape and cities has to be optimized in order to save money and enable coverage of signals at all places. An optimizing has also to be made when windmills are built in order to produce electricity. Planning for roads and railways is to be done with the goal that a minimum of earth masses has to be moved. All such planning of construction work requires knowledge about the elevations in the area. It is the work of photogrammetrists and surveyors to measure elevations and to produce a model of the area which then can be handled by a computer. This Digital Elevation Model (DEM) is formed by means of many single points and mathematical formulae are used to determine the elevation of other points in between. The density of measured points and the measuring device determine the accuracy of the DEM.

Digital Elevation Models have become important in many countries. The reasons are manifold. The dangers of flooding and construction activities mentioned above are only a few of the reasons. New demands to DEMs are raised by the user. For example, the actuality of the DEM data is of importance in most of the applications. Updating of DEM data is therefore a big need. The way how this should be done is not very clear in the mapping organizations. Several methods are at disposal. Photogrammetry and laser scanning are used when high accuracy and high density are required. Both technologies are still undergoing many changes. Research in this field is currently going on at universities as well as in industry. Digital Elevation Models cover a wide field of knowledge; many details belong to different technologies. There is always a desire for improving the production of the DEMs and to find new uses for the data. DEMs as well as many other geo-data have become expensive in recent years.

In Denmark, working with DEMs has a long tradition, both at universities and in practice. The whole country is completely covered by DEMs of different accuracy and density. DEMs are applied for the production of orthoimages and 3D photo-realistic models of the landscape and cities. Mapping and updating of maps is now possible by means of DEMs and single aerial images. DEMs have become an important part of Denmark's geospatial data infrastructure.

The development of DEMs has a long history. The author has had the opportunity to participate in the development for more than 40 years. He has followed them from practice as well as from the research point view. His contributions have to be evaluated in the context of the times they were presented. Many things are done differently today. But the latest developments in the field of Digital Elevation Models are also dealt with in this thesis. The following description of the developments in DTMs will therefore mention the contributions of the author in the past and end with his contributions of the last few years. **This thesis is the work of his professional career.**

1.1 Existing publications and research

Recent books on this subject are the "Digital Elevation Model Technologies and Application – The DEM Users Manual" (Maune 2007) and "Digital Terrain Modeling" (Li et al. 2005). The first book comprises 655 pages and is a manual; the second is a text book with 323 pages. They deal with the fundamentals and cover all data acquisition systems. The photogrammetric technology is discussed rather shortly. The list of references comprises in the case of the manual 12 pages. Another text book is the Danish "Book on GIS and geo-data" (Balstrøm et al. 2006) which also contains a chapter on photogrammetry with six pages.

Research work on the topic "Generation and application of DEMs" is extensive. The methodology in the generation of DEMs has changed a lot over the years. Already from the early days of map making there existed the need to improve the economy and the speed of the production. One possibility for higher efficiency is to increase the distance between the terrain and the sensor. High flying heights (above 4km) create safety problems for the flying crew. If the sensor is placed behind a window, then problems in the evaluation have to be overcome. These problems of high-altitude photography have been studied in (Gut&Höhle 1977). Accurate results could be reached with film-based cameras and analogue stereo-plotters.

Cameras and scanners can also be placed in satellites. The Indian Cartosat-1, for example, takes stereo imagery from an altitude of 618km (GSD=2.5m) and DEMs with a vertical accuracy of RMSE=3.2m can be derived (Jacobsen et al. 2008). The latest satellite-based sensors (for example WorldView-1) have smaller GSDs and possibly enable DEMs with RMSE=1m.

The distance between the sampled elevations effects the accuracy of the DEM. Research work of O. Jacobi at Denmarks Technical University (DTU) gave an answer to the question "What distance between points must be selected in order to achieve a required DEM accuracy for a certain terrain type and sensor" (Jacobi 1977). The automated determination of the elevations by means of a hardware correlator has been investigated at DTU (Eeg et al. 1990). The scanning of analogue images in an analytical plotter using a hardware correlator did, however, not survive. The appearance of digital cameras, new correlation and filtering techniques promised better results.

During the author's time at Aalborg University (since 1986) he has had opportunities to work extensively with the generation and application of DEMs. The photogrammetric method for generating, checking and updating of DEMs became the core of his scientific work. The application of DEMs for orthoimage production, mapping by means of single oblique images and DEMs, and a few other new applications were thoroughly investigated at an early point of time.

The author also initiated the research work of others. The PhD students B. Møller Pedersen, M. Wind and M. Potuckova investigated parts of this topic at AAU and contributed with ideas and solutions. V. Kralova, TU Prague, who did a major part of her PhD thesis under the guidance of the author at AAU, dealt with the generation of photo-realistic city models from oblique images taken from air and ground in her thesis.

In the following sections some of the current problems with the generation and application of DEMs are defined and the goals of this contribution are set out.

1.2 Definition of problem areas and goals of the thesis

The users of DEM data need to know what the characteristics of such data are. Only then can they avoid mistakes in using the DEM data in their application. There are many different applications. Each one has its own demands. The producers of the data have to be aware of their customers' demands and then use the most effective production method in order to successfully compete on the market for such tasks. There are new methods and new tools all the time. The situation is unclear at the moment as to which method is optimal. This thesis will therefore try to give answers to major questions of today regarding the generation and application of DTMs. The photogrammetric method has a long tradition in the generation of DEMs. Problems had to be solved in generation and application of DEMs in each period of development. Many people have contributed to this development. The author of this thesis has worked within some areas and could contribute with some innovations, mainly in the field of photogrammetry. But in recent years many innovations have occurred in aerial photogrammetry. This thesis will focus on the generation and application by means of the innovations in digital aerial photogrammetry.

Other methods of acquisition have come up in the last few years: Laser scanning, interferometric SAR, and satellite-based stereo-photogrammetry. Laser scanning will also be discussed in this thesis. Interferometric SAR and satellite-based photogrammetry are technologies which are important for some applications. Their potential for high accuracy is less than in aerial photogrammetry and laser scanning. The **goal of the thesis** is to present the author's research on the generation and application of DEMs and to create a comprehensive view of his contributions in order to render them applicable to the demands of today. Furthermore, the position of photogrammetry in relation to laser scanning, interferometric SAR and hydrography for the generation and application of DEMs will be defined.

The thesis deals mainly with the author's **recent** research work. It is by no means a textbook or a manual. The attached list of his publications covers 54 publications (articles in journals, conference proceedings, and research reports). Each one has its own problem, solution, and references.

1.3 Contents and structure

The thesis consists of two parts. The first part contains a summary of previous and new investigations and the second part (appendix) ten important articles published in English in scientific journals and conference proceedings. The introduction has defined problem areas under discussion and the goals of the thesis. After the introduction the "Generation of DEMs" is presented, first dealing with older contributions by the author, and secondly, with the author's latest research regarding the generation of DEMs by means of digital large format frame cameras and new software tools. It is structured with a view to the steps of the production process. The author's publications are presented by a summarizing text and a few characteristic figures.

The third major chapter deals with "Applications of DTMs", especially those where the author has contributed with some innovations.

Some economic considerations are mentioned in Chapter 4 and user requirements are analyzed in Chapter 5. The answers to the current problem areas of DTMs are given in Chapter 6 followed by a conclusion. The abstract and the Danish 'sammendrag' sum up this thesis and contain a summarizing statement of the achieved research results.

The titles of the articles contained in the appendix are typed with bold letters in the first part of the thesis.

2. The generation of Digital Elevation Models

Models are made to describe the real world. This can only be done by some generalizations. The three-dimensional landscape can be approximated by a regular grid (raster) of elevations. Triangles with elevations at each corner can also approximate the terrain and the objects above terrain (buildings, trees, etc.). The collection of all points is then the model of the surface and is called Digital Surface Model (DSM). If the model describes only the terrain, the 'bare earth', it is called a Digital Terrain Model (DTM). Both models, the DSM and the DTM, are Digital Elevation Models (DEMs). Both models have their own requirements and applications. In this thesis, it is mainly the DTM, which is dealt with, especially its generation and its application.

For many years the terrain heights were determined by means of manual photogrammetry. An operator measured contour lines and supplemented them with spot heights and break lines. Drawing of contour lines in flat areas or forested areas is difficult and time consuming. In order to overcome these difficulties and to achieve higher production rates other methods were required. Elevations were then measured in profiles and a photogrammetric system guided the operator from point to point where he or she had to measure the elevations. This dull operation was later automated and the measurement of the heights was carried out by computers.

The basis of such automated measurement of elevations is the matching of corresponding image parts. Image matching became the central part of the photogrammetric research. Recent developments made the DTM generation more accurate and more reliable. Main cause is the availability of digital large format cameras and advances in the correlation techniques. The automatically measured elevations can be on top of houses, trees, cars, etc. A classification program has to separate the off ground points from the points on the ground. There may be blunders among the derived elevations. They have to be detected and eliminated. Areas without elevations (gaps) will occur, and they have to be filled by interpolation so that a complete and regular grid of elevations can be generated. The result is the Digital Terrain Model. The DTM has then to be evaluated and measures for accuracy and completeness have to be found. Finally, the DTM has also to be updated because the landscape changes due to construction activities and erosion.

In recent years airborne laser scanning has become important as acquisition method for Digital Elevation Models. Especially in forested areas it is of advantage to use laser scanning as acquisition method. Laser scanning as well as digital photogrammetry can collect DEMs with a high density. From a dense point cloud DSMs and DTMs can be derived.

The research activities of the author regarding DTMs started already in 1967. The **mapping of contour lines in flat areas** was investigated (Höhle 1967). The standard deviation of the 0.5m contour lines (derived by an operator from large format photographs of the scale 1:7600) was 19 cm or 0.16‰ of the flying altitude. The Figure 1 depicts profiles through three DTMs derived by photogrammetry and tachymetry. In addition, short profiles were measured by levelling in order to derive the roughness of various terrain types (fields, meadows). The investigations made clear that measurement of single points cannot be better than RMSE=0.05m due to roughness of the terrain.

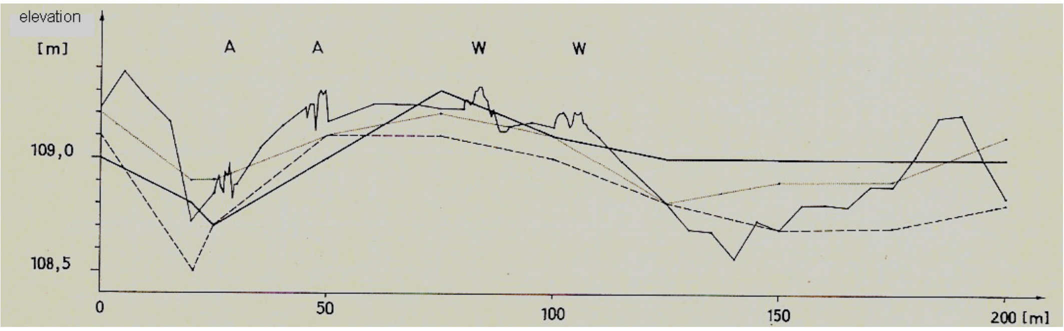


Figure 1. Elevation profiles through DTMs determined by photogrammetry and field measurements. It means: A…5m profiles over field, W…5 m profiles over meadow

┈┈ elevations by levelling
—— DTM by tachymetry
- - - - - DTM from photos 1:5800
┈┈ DTM from photos 1:7600

Taken from (Höhle 1967)

In the seventies the author was involved in the generation of **DTMs for orthophoto production**. Elevation profiles were scanned by an operator in a stereo plotter and the orthophoto was produced simultaneously (on-line). Another type of orthophoto instrument was controlled from a stored DTM (off-line). Beside problem-solving in calibration and use of the photogrammetric systems the author became involved in quality and economic issues of DTM generation. Several publications are from this period, e.g. (Höhle 1973), (Höhle&Schneider 1973), (Höhle&Stewardson 1977), and (Höhle&Pohjola 1983). Visualization of the DTM by contour lines and their plotting by means of digital plotting tables was a task in the beginning of the eighties. The performance parameters of the designed and produced digital plotting tables (accuracy, line quality, working speed and software functions) were investigated in (Höhle 1983).

The **determination of a DTM at seas and lakes** is an important task of mapping agencies. Shallow water areas can also be surveyed by means of optical methods like photogrammetry and laser scanning. The refraction of the imaging rays at the border between water and air has to be taken into account mathematically. If standard photogrammetric instrumentation is used, corrections to the measured apparent depths have to be applied in order to obtain true water depths (cf. Figure 2). Such correction formulae have been developed and tested by the author (Höhle 1988).

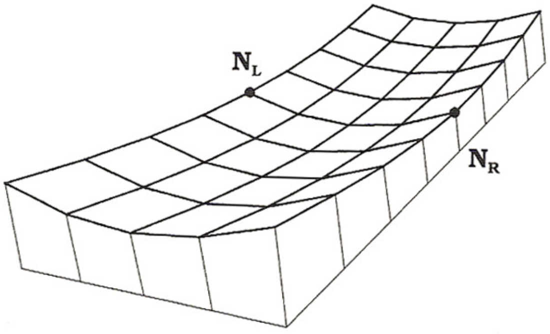


Figure 2.

A plane DTM of the sea bottom will be warped if measured in a standard photogrammetric device. Corrections to the measured apparent depths have to be applied in order to obtain true water depths.

It means: N_L, N_R…Nadir points of the two photographs forming a stereo-pair

Taken from (Höhle 1994)

Laser scanners with two types of lasers (using green and near infrared light) seem to become a solution for surveying of the shallow underwater terrain too. Deep depths have to be surveyed by means of hydrographic methods which use sound instead of light. An overview about the different surveying methods of underwater DTMs is given in "**Application of Terrain Modelling in Coastal Areas"** (Höhle 1986, **A10**).

The author did extensive research on the photogrammetric determination of water depths. Practical trials were carried out at Danish coasts. The achievable accuracy by photogrammetry depends on the transparency of the water body and the calmness of the water surface. Texture of the underwater terrain is needed for good results. More details on this research of DTM generation of underwater terrain is contained in (Höhle 1971) and in chapter 2.9.

Part of this mapping is the **determination of the coast line**. The definition of the coast line is different for land maps and nautical charts. In the first case the Mean Higher High Water (MHHW) and in the second case the Mean Lower Low Water (MLLW) have been used for the determination of the coast line. Another definition uses the zero elevation of the National Vertical Datum. Whatever the definition of the coast line is, it can be derived numerically from the DTM including land and sea areas. The coast line can also be traced directly from stereo pairs as it was practiced in (Höhle 1990b).

The generation and application of **object-oriented DTMs** became another research topic for the author at Aalborg University (AAU). The objects are spot elevations, break- and drain lines, obscured areas, etc. (cf. Figure 3). They are extracted from existing vector databases and contribute to the generation of DTMs. All objects have attributes and the data are topologically structured. The objects and their attributes can be analyzed in a Geographic Information System (GIS). Furthermore, many new applications and products can be created (cf. chapter 3.2). More details on object-oriented DTMs and their use in Geographic Information Systems (GIS) are published in (Höhle 1992) and (Höhle 1993a/b).

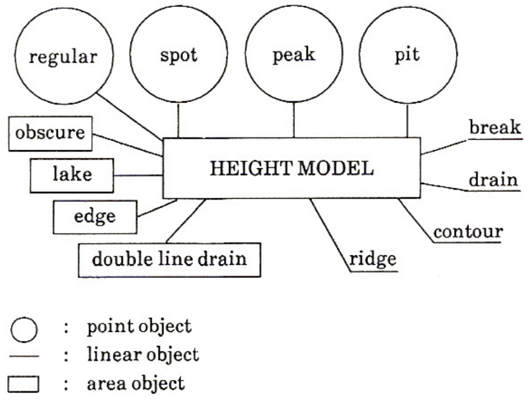


Figure 3.
The objects of the theme "Height model". All objects can have attributes and topology.

Taken from (Höhle1993a/b)

The **3D city models** include building models, DTMs and other models (e.g. for traffic, vegetation, street features). There are different types of 3D city models. They differ in complexity and accuracy. The simplest form is a wire frame model, which can be derived from existing maps and terrestrial images. The wire frame model can be rendered using terrestrial images. The result is a photo-realistic model. Details on the methodology is published in (Höhle 1995) and (Höhle 1996c).

The cooperation with Professor G. Pomaska, University of Applied Sciences Bielefeld, Germany, and the author has resulted in several projects of this kind. The solutions were based on ground surveying and terrestrial photogrammetry, cf. (Höhle&Pomaska 2000a/b). Oblique images from the air and from the ground were used to derive a photo-realistic model of a city in Iraque (Kralova 2008), (Höhle et al., 2008b).

A great deal of automation is necessary to produce 3D models of large cities in a short time. The source data are large-scale vector maps with the peripheral lines of buildings, the DTM, terrestrial and aerial images. Roofs have to be added. They can be simple or sophisticated. Advanced 3D city models are object-oriented and photo-realistic.

The transition from film-based images to digital images created new possibilities for the automation of DEM generation. The matching of corresponding image patches became the key to the solution of this task.

First research by the author regarding matching techniques was carried out in **"The automatic measurement of targets"** (Höhle 1997a, **A8**). The formula and procedures for measuring image positions of targets by means of a template were derived and tested with simulated and real images. An accuracy of σ=0.24 pixel has been achieved for real images. Investigations how blunders could be avoided were also carried out. On the basis of the experiences with matching, the automatic generation of DEMs by means of aerial images was chosen as a research topic.

Furthermore, several **interactive learning programs** dealing with matching techniques and its applications were developed under the guidance of the author, e.g. "LDIP", “Ortho”, “LDIPinter”, “LDIPinter2”, and “AutoOrient”, which generations of students at AAU and elsewhere used in their training in digital photogrammetry. The dissemination of new knowledge by means of interactive learning programs has accompanied the author’s research since 1986. Several of his publications deal with the subject of e-learning, e.g. Höhle 1997c. The interactive learning programs “LDIP” and “Ortho” received the “Golden Award” at the software contest for educational material (“Catcon”) of the International Society for Photogrammetry and Remote Sensing (ISPRS) in 1996 and “LDIPInter” got the “Silver Award” in 2000. The mentioned learning programs can all be accessed at the address:

http://people.plan.aau.dk/~jh/cal.htm.

In the following, the author’s **latest contributions** regarding research in “Generation and application of Digital Elevation Models” are presented. The various steps in the DEM generation are explained and used as disposition. In this way the publications and some of the unpublished work are brought into context.

2.1 Data acquisition by digital large format frame cameras

Accurate results in photogrammetric DEM generation can be obtained when using large format cameras. It is also an economic approach. Presently the digital cameras can not be built with the standard format of film-based cameras (230mm x 230mm). Several sensor elements (CCDs) had to be combined in order to achieve relatively large image sizes, for example of 165.9mm x 92.2mm (Intergraph’s DMC) or 103.5mm x 67.5mm (Microsoft’s UltraCam$_D$). This is only 29% and respectively 13% of the area of the standard format. The format of the new digital large frame cameras is not squared and the smaller frame size is normally placed in the direction of flight (cf. Figure 4). This results in smaller base to height ratios at these cameras (b/h=0.31 at 60% overlapping images for the DMC and 0.27 for the UltraCam$_D$ respectively) compared to b/h=0.60 at film based cameras with wide-angle lenses.

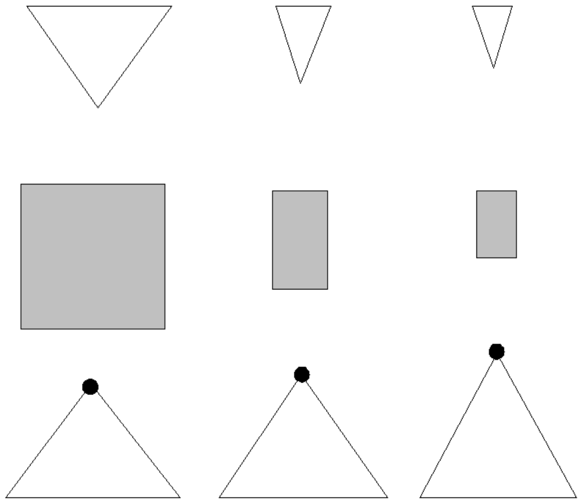


Figure 4.

Characteristics of large format aerial cameras.

The symbols mean:

From left to right: Standard wide angle camera, digital cameras DMC and UltraCam$_D$

From top to bottom: Field of view (FOV) in the direction of flight, format, flying height for the same Ground Sampling Distance (GSD) and FOV across the direction of flight

The factor h/b determines the height accuracy according to formula

$\sigma_h = h/b \cdot m_b \cdot \sigma_{px'}$ (1)

where

σ_h… height accuracy (standard deviation)
m_b… image scale figure
$\sigma_{px'}$… parallax accuracy (standard deviation)
h… flying height above average terrain
b… base or distance between the two overlapping images forming a stereo pair

It can be seen that the film-based cameras of the standard format use a better geometry (a smaller factor h/b) for the determination of elevations. The other factor influencing the height accuracy is the parallax accuracy. In the publication **"DEM generation using a digital large format frame camera"** this factor was derived from tests with the UltraCam_D camera with $\sigma_{px'} = 6\mu m$ (Höhle 2009, **A2**). In recent tests with the DMC camera the parallax accuracy resulted in $\sigma_{px'} = 4.4\mu m$. It is the mean derived from GSD=10 cm and from GSD=20 cm imagery. The check- and control points had a superior accuracy and were well defined.

Other important characteristics of the digital cameras are the camera constant and the size of the pixel (pel) in the image plane. If the landscape has to be imaged with a certain Ground Sampling Distance (GSD), the image scale figure is given by

$m_b = GSD / pel$

The pixel of the DMC camera is 12µm or 0.012mm. The image scale figure for images with GSD=10cm is then

$m_b = 100mm / 0.012mm = 8333$

The flying height above ground is calculated by

$h = c \cdot m_b$ (2)

Regarding our example, the photography will be taken from h=1000m.

The achievable accuracy for elevations by means of images of the digital camera DMC taken with a ground sampling distance of GSD=10cm is about

$\sigma_h = 3.23 \cdot 8\,333 \cdot 0.0044mm = 118mm \approx 12cm$

The relative accuracy, in per thousand of the flying height, is then

$\sigma_h/h = 0.12‰$

Digital cameras have a high radiometric resolution (number of gray values). Thus, details in the shadows can be detected. But more important for the DEM generation is the fact that the parallaxes between corresponding image patches can automatically be measured with a high accuracy. This fact is responsible for that the digital large format frame cameras can produce a high accuracy for elevations.

The width of the covered area by one strip is also an important characteristic of the digital camera. It is an economic factor. The width of the flown strip (w) is calculated when multiplying the large side of the image (s_q) by the image scale figure (m_b).

$w=s_q \cdot m_b$

The width of the strip for GSD=10cm images is for the selected example

$w=165.9\text{mm} \cdot 8333 \approx 1382\text{m}$

Other flight parameters concern the overlap of images. The usual values are a forward overlap of 60% and 20% side lap. The accuracy can be improved when higher overlaps are selected so that the elevations can be determined from several images. Figure 5 depicts an image together with the centres of four overlapping images and Table 1 shows base/height ratios for various combinations of image pairs.

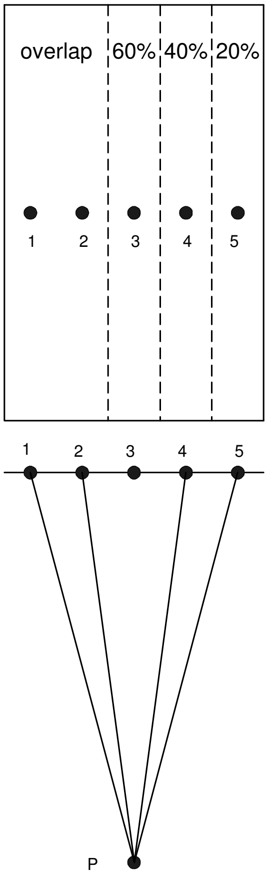


Figure 5.
Multiple image pairs may be used to determine the elevation of an object point (P). For image pairs with less overlap the base/height ratio is increased and the accuracy of the elevation is improved.

Image pair	overlap	base/height ratio
1,5	20 %	1/1.9
1,4	40 %	1/2.5
2,5	40 %	1/2.5
2,4	60 %	1/3.7

Table 1. Image pair combinations and the base/height ratios of the digital large format camera UltraCam_D.

The images of the DMC camera are produced by means of four tilted cameras. The single images are corrected for lens distortion and other image deformations. They are, thereafter, rectified and fused together by means of correlation. This virtual image is panchromatic and of a high geometric resolution. A normal colour image is produced by means of three additional images containing the red, green and blue spectral band in a smaller scale. This colouring of the panchromatic image is called ‘pansharpening’. For recognizing of objects colour images are better than panchromatic images. This artificial image is used in the further processing. The geometric quality of the image is important for the accuracy of the DTM. The calibration data of the camera are given in the calibration report of the manufacturer.

The investigation **“DEM generation using a digital large format frame camera”**, published in (Höhle 2009, **A2**) is based on the digital large format frame camera ‘UltraCam_D‘ of Microsoft Photogrammetry. The performance parameters of photogrammetric DEM generation were analyzed. Regarding the digital camera, it was found that the unfavourable base/height ratio can be compensated by high parallax accuracy. By means of a given formula the required flying height for a specified vertical accuracy can be calculated using this value for the parallax accuracy. This contribution to the planning of a DEM project is of practical value. New developments in cameras and processing software are discussed and a comparison between photogrammetry and airborne laser scanning is made.

2.2 Orientation of aerial images

The exterior orientation of the aerial images is usually determined by means of aero-triangulation using a few ground control points. In recent years it has been possible to measure the position and the attitude of the images by a Global Positioning System (GPS) and an Inertial Measurement Unit (IMU). This direct georeferencing of aerial images is currently not accurate enough for DEM generation. The combined use of aero-triangulation and GPS/IMU data, the so-called integrated sensor orientation, is the better way to go. Research on this approach is published, for example in (Heipke et al. 2002). Some ground control points are still necessary. They are usually determined by Real Time Kinematic (RTK) satellite navigation using the GPS signal. In forested areas, however, an electronic tachymeter may have to be applied.

Another approach uses existing databases. Existing vector maps, DTMs and orthoimages are used for the derivation of the exterior orientation parameters of new aerial images. Thus, the procedures can be automated to a large extent. Research in the field of **"Automatic orientation of aerial images"** has been initiated and carried out in (Höhle 2002, **A6**). The achievable accuracy depends on the existence of time-invariant objects in the area. Road crosses in the open land and manhole covers and drain gratings in the built-up areas can be used as ground control. The search for the corresponding image content depends on the quality of approximate values for the orientation. Matching of image patches of the orthoimage with parts of the aerial image leads to accurate image positions. The final orientation parameters are derived by bundle adjustment. When using road crosses as objects, the georeferencing of aerial images can be done fully automatically (cf. Figure 6). The achieved accuracy in a test using small scale images (m_b=27 000) of a wide-angle camera, an orthoimage with GSD=0.8m, a DTM with a vertical accuracy of σ=0.5m, and a grid spacing of Δ=20m was σ = 33µm in the image plane, which corresponded to an angular value of 14mgon (Höhle 1999b), (Höhle 2001).

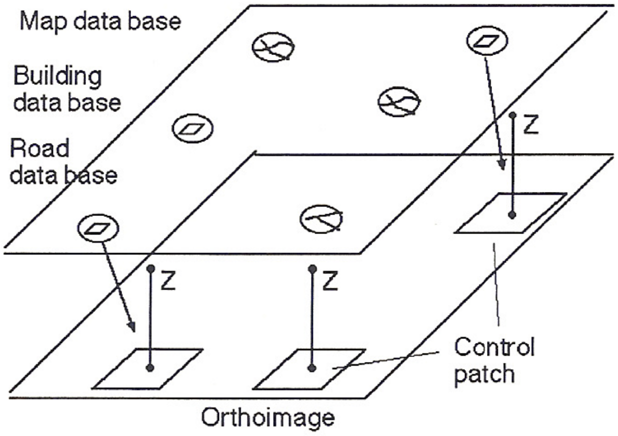


Figure 6.
Road crosses or buildings extracted from existing databases can be used as templates (control patches) in the matching with patches of a new aerial image. The elevations (Z-values) of the objects are derived from an existing DTM.

(Taken from Höhle1999b)

The demands on the orientation parameters to be used for the generation of precision DEMs are high. For examples, if an error exists in the longitudinal tilt (dφ), the error in elevation is estimated by the formula

$$dh \approx \frac{h^2 + b^2}{b} \cdot d\varphi \,,$$

where

dh… error in elevation at the side of the stereo model
b… basis
h… flying altitude above average terrain
dφ… error in longitudinal tilt

At the digital large format frame camera with pel=12μm, c=120mm, flown with 60% overlap and GSD=10 cm (resulting in h=1000m, b=307m) an error of dφ=1mgon already amounts to an elevation error of dh=6cm at the side of the stereo model (cf. Figure 7). Other objects may have to be selected for the matching, e.g. manhole covers or drain gratings. Such objects are well defined and time-invariant. The application of the proposed method is restricted to towns and large scale imagery.

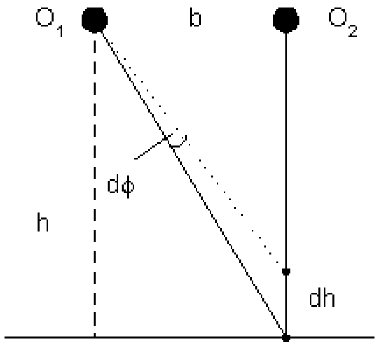


Figure 7.
Influence of an error in the orientation angle (dφ) on the elevation at the side of the stereo model.

It means: dh... elevation error,
dφ... orientation error,
b... basis,
h... flying altitude,
O_1, O_2...perspective centres

Other publications of the author on the topic of "Automatic Orientation of aerial images by means of existing orthoimages and height data" were (Höhle 1998), (Höhle 1999b).

The European Organization for Experimental Photogrammetric Research (OEEPE/EuroSDR) initiated the test "Orientation of aerial images on database information" in which several research groups participated. The author was leader of this research project and analyzed the results of seven researchers. The test and its results were published in OEEPE's official publication (Höhle 1999a).

An international seminar with the same topic was held at AAU, where specialists presented new methods and results. PhD work at AAU on the subject was carried out by Bjarke M. Pedersen and Marketa Potuckova under the guidance of the author (Potuckova 2006).

Furthermore, the techniques in the automated orientation of aerial images by means of existing database information and the achieved results of the tests were later disseminated in two e-learning courses of OEEPE/EuroSDR (Höhle, 2002).

2.3 Generation of point clouds and gridded DEMs

Matching of imagery is used in the automatic generation of DEMs. A lot of research has taken place over the years on matching image patches of a stereo pair. The task is not simple because mismatches can occur when the imagery lacks texture and when the corresponding image patches have differences in scale and content. The DEMs may therefore have blunders and gaps. Such areas have to be corrected and supplemented with new elevations. The automatically generated point clouds can be very dense. They have a high accuracy in elevation as well as in position and are produced very economically. The methodology of deriving gridded DEMs by means of automated photogrammetry is depicted in Figure 8.

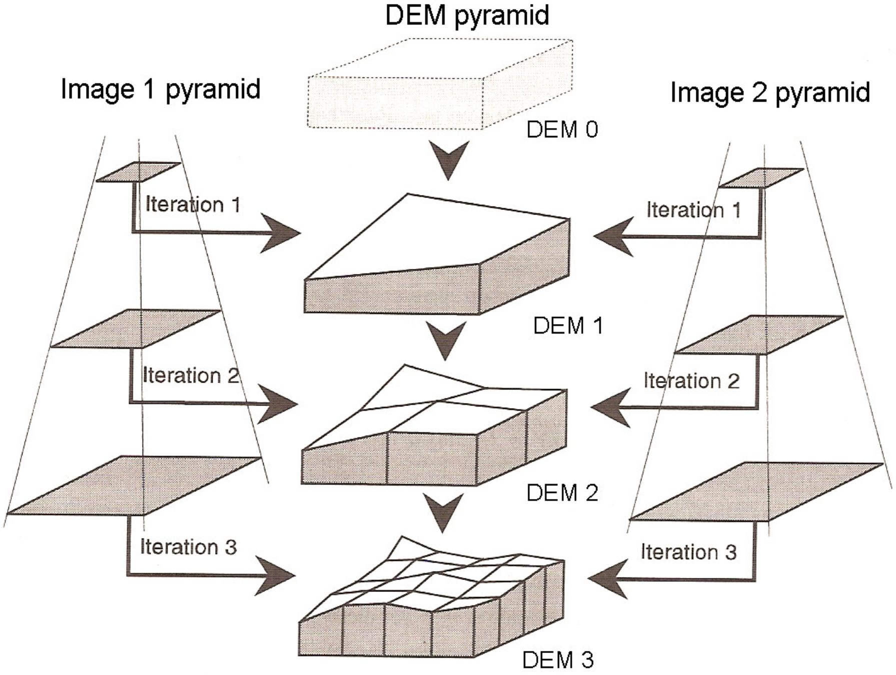


Figure 8. DEM generation by means of automated photogrammetry. Corresponding parts of image 1 and image 2 are matched using features and intensity values. The result is a point cloud which is transferred to a regular grid by interpolation. The accuracy and density of the DEM is improved from iteration to iteration using higher and higher resolution in the overlapping images.

Taken from (Kraus 1996)

Elevations are determined not only on the terrain, but also on top of buildings, vegetation and other elevated objects. The elevations of temporary objects like vehicles, animals, persons, hay stacks etc. have to be removed. Classification in terrain and off-terrain points is therefore necessary. Filtering can already take place in the DEM generation. A Digital Surface Model and a Digital Terrain Model can be produced from the same point cloud.

The derivation of DEMs requires the setting of various parameters. For example, the selection of the parallax bound, the minimum correlation coefficient, and the weights for the interpolation of the grid will influence the result. Additional information can be chosen in order to exclude areas from the calculation, to use approximations of the DEM as start values, and to use morphological data like break lines. In this way, the generation of DEMs is supported, and more accurate and more reliable results are obtained.

Research regarding the derivation of DEMs was initiated by the author in 1996. At that time digital cameras were not yet at disposal and aerial photographs had, therefore, to be digitized by a precision scanner. The influence of pixel size, flying height and grid size on the accuracy of the DEM had to be investigated and was subject of a PhD thesis at AAU (Wind 2008).

2.4 Filtering and classification

The editing of the derived DEM data can be done in three ways:

-displaying all points with low redundancy, poor accuracy, and points at border areas
-removing of elevations within areas of elevated objects (buildings, trees, etc.)
-filtering for blunders, and
-classification into terrain points and off-terrain points.

The derived indicators for poor accuracy represent only an ‘internal accuracy’. They do not necessarily correspond to the ‘external accuracy’ determined by accurate reference values. Such areas should be checked visually by an operator using stereo vision.

Existing topographic databases can be used to find buildings and other elevated area objects. The elevations of such areas can then be removed. A buffer zone around the elevated area object may be useful if planimetric errors exist.

Filtering of the DEM should first of all detect and remove gross errors. A threshold for the deviations from an internal DTM has to be defined as a parameter. The classification into ground points and off-ground points is realized by so called object filters. Filters for buildings use the parameters cell size, minimum area of the building, and minimum slope. A vegetation filter uses four parameters: two different cell sizes and two heights. The cell size is used for the interpolation of the internal DTM, which is then used to analyze the point cloud. It is selected larger than the size of the derived DTM. The meaning of the various parameters is explained by means of graphics in Table 2.

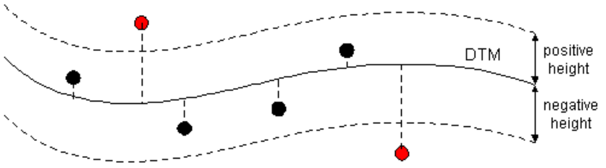
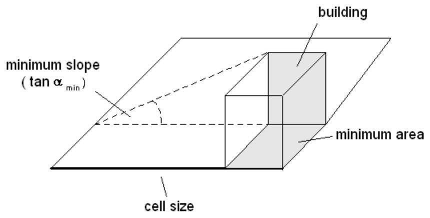
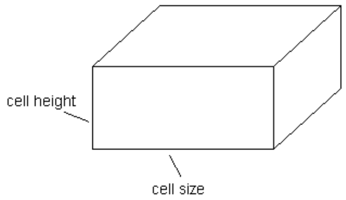
filter	parameters	graphics
gross error	positive height negative height	
building	cell size minimum slope minimum area	
vegetation	cell size 1 cell height 1 cell size 2 cell height 2	

Table 2. Filters and their parameters for editing of DEMs

The filters can be applied separately or combined for a region or for the whole project. Manual trials are necessary in order to find proper values for the filter parameters for the type of imagery and terrain to be processed.

The Figure 9 shows an example of such a filtering of DEM data derived by digital photogrammetry. The applied filters classified elevations as terrain points (blue colour) and off-terrain points or gross errors (red colour).

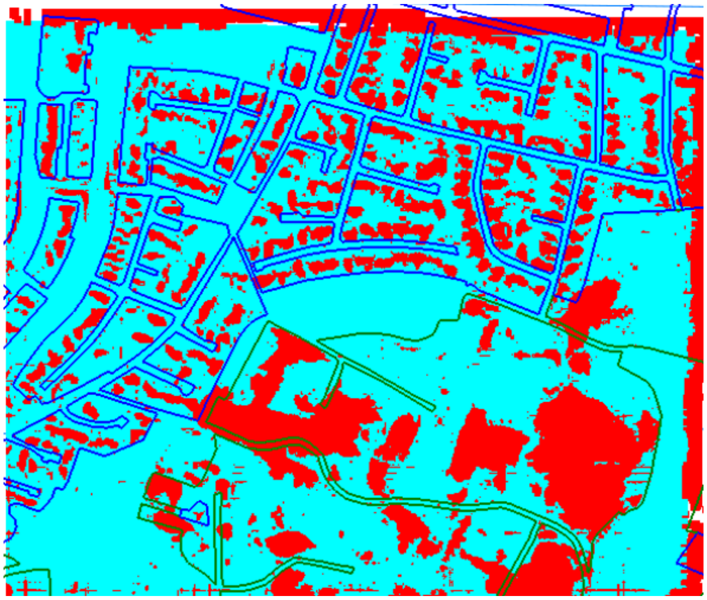


Figure 9.
Result of filtering. All elevations in the red areas will not be used in the DTM calculation

Taken from (Höhle 2009b)

2.5 Completion of Digital Terrain Models (DTMs)

The DTM should have a complete regular grid which means that the elevations removed by the filtering have to be replaced by new ones using the remaining terrain points as support in the interpolation. A maximum 'gap distance' has to be specified. By this completion new errors may eventually be introduced and/or gaps will remain.
Other data have to be merged with the automatically generated and filtered DTM. Until now all the operations are computer-based and can be carried out more or less automatically.

Manual work should be avoided because of cost. Nevertheless there may be manual work to be done in order to complete the DTM. The anticipated application may have special requirements on the content and quality of the DTM. The production of orthophotos, for example, requires the modelling of bridges or other important objects above terrain (cf. chapter 5.1).

2.6 Modelling of objects above terrain

The DTM with its regular grid has to be supplemented with elevations of some objects above terrain. Bridges in the orthoimage, for example, have to be imaged at the correct position and without deformations. Therefore, the edges of the bridge have to be mapped in 3D. Other objects are buildings. The modelling of buildings is accomplished by photogrammetry too. Different levels of details can be created. The generation of a 3D city model with the accurate representation of the roofs requires the interactive mapping of the roof lines. 3D city models with such a level of detail are the prerequisites for the derivation of 'true orthoimages'. More details on this application are contained in chapter 3.1. A DTM with modelled objects is a so called blended DTM. It contains the grid points as well as the intersections of break lines with grid lines.

2.7 Checking of the accuracy

The accuracy of DTMs concerns the vertical and the horizontal accuracy. The **vertical accuracy** is dealt with first.

It was already pointed out in section 2.3 that DTMs derived by digital photogrammetry (or by laser scanning) may have gross errors. Also non-normality in the distribution of errors is usually present. Robust accuracy measures taking these phenomena into account should therefore be applied. The number of checkpoints should be high enough to ensure sufficiently small confidence intervals of the estimated accuracy measures. Furthermore, the accuracy measures have to be derived for various types of terrain because different conditions exist. For example, the elevations in dense forests cannot be measured directly. They are derived from adjacent elevations by means of filtering and interpolation.

The applied robust accuracy measures are based on the median, the Normalized Median Absolute Deviation (NMAD) or the quantiles of the error distribution. In comparison to the standard measures like Root Mean Square Error (RMSE), mean, and standard deviation such robust measures are not influenced by gross errors. The NMAD value corresponds to the standard deviation when a normal distribution of the errors is present. Figure 10 explains graphically what these robust measures mean in relation to the standard measures.

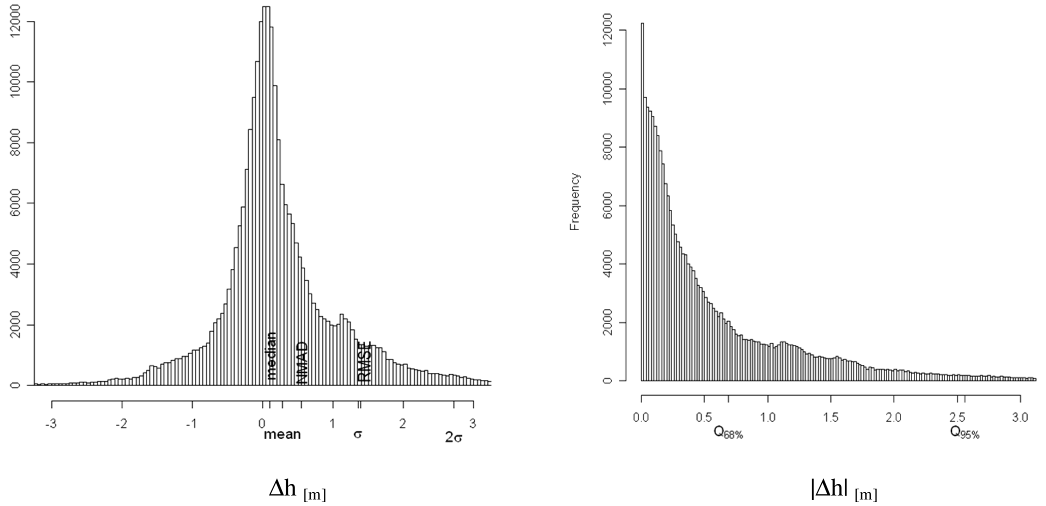


Figure 10. Frequency of elevation errors. Robust accuracy measures (median, NMAD and 68% and 95% quantiles) are plotted together with the standard accuracy measures (RMSE, mean, standard deviation) for a case where non-normal distribution of errors (Δh and $|\Delta h|$) exist.

In the publication **"Accuracy assessment of Digital Elevation Models by means of robust statistical methods"** (Höhle & Höhle 2009, **A1**) robust accuracy measures are proposed by the authors and applied at several examples of DEMs containing blunders and non-normality of error distribution. Also, equations for the number of necessary checkpoints are derived based on the statistical sample size theory.

In recent tests with photogrammetric DEM generation the author applied the robust accuracy measures and demonstrated their usefulness (Höhle 2009). The achieved results revealed high accuracy for photogrammetrically derived DTMs in the NMAD values (18 cm in open area, 43 cm for built-up area and 30 cm for forested area) when GSD=20 cm images of a DMC camera were used. The accuracies are derived by means of about 135 checkpoints of superior accuracy. They are determined by ground measurements using the GPS/RTK method.

The efforts for ground measurements are high. Checking of extensive areas has to use more economic but nevertheless accurate methods for the quality control of DEMs. Research in checking and updating of DEMs has been initiated by the author. **The EuroSDR project "Automated checking and improving of digital terrain models"** evaluated various methods and results of different authors by means of the same test material (Höhle 2006), (Höhle 2007, **A4**).

In this connection the PhD project of M. Potuckova has to be mentioned, which was carried out at AAU under the guidance of the author (Potuckova 2006). The applied method uses two orthoimages, which are derived from two overlapping images, and measures parallaxes between corresponding image parts **automatically**. Parallaxes only exist when the DTM, which was used in the orthoimage generation, had deviations from the true ground (cf. Figure 11).

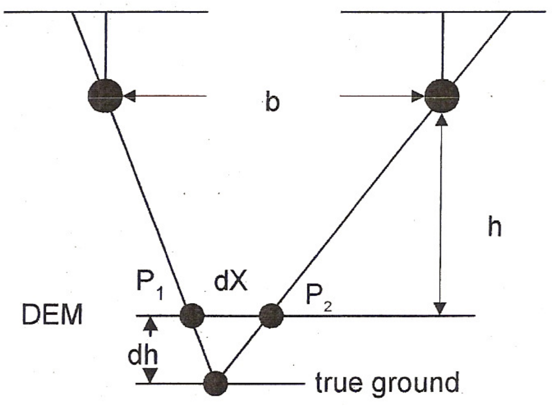


Figure 11.
Checking of the DEM by means of two orthoimages. An error in the DEM (dh) results in a parallax (dX) between the two orthoimages, which are derived from the left and the right aerial image.

It means:
h…flying height above DEM
b…distance between two images (basis)
P_1, P_2…object point imaged in two orthoimages

These DTM errors can be found by formula (3).

$$dh \approx \left(dX \cdot \frac{h}{b} \right) + \left(dX \cdot \frac{h}{b} \right)^2 \cdot \frac{1}{h} \qquad (3)$$

where

dh… elevation error
h… height above DEM
b… basis
dX…parallax between two corresponding orthoimage patches

The method depends on texture in the orthoimages and on accurate orientation data. A low flight altitude can be selected in order to obtain the necessary accuracy. In order to avoid blunders in the correlation, thresholds for similarity measures are applied. Detailed studies showed that a combination of thresholds for the maximum correlation coefficient, the average mutual information, and the 'distance' of intensity values between the two images can reduce the number of blunders in the automated measurements. More details on this research can be found in the peer reviewed publication **"Automated quality control for orthoimages and DEMs"** (Höhle&Potuckova 2005a, **A5**).

It should be mentioned that the accuracy of an existing DEM can also be improved by means of this "Two-orthophoto- method". The automatically derived elevation errors at all grid points may be used as corrections for the DEM. Prerequisite for improvements is that the applied corrections have the necessary accuracy.

The checking of the **horizontal or planimetric accuracy** is more difficult to accomplish than the vertical accuracy. Planimetric errors will also produce vertical errors if the terrain has slopes and height differences, for example at buildings. Source of planimetric errors is orientation errors of the sensor, measuring errors, and different definitions of the origo in the exchange formats. The checking of the planimetric accuracy is therefore important.

A few check points have to be used. The reference values are determined in the aerotriangulation or by mapping them from image pairs. They are then compared with the values derived from intersecting of planes and lines at house roofs. Details of the method are given in section 2.10. In general the planimetric errors at the photogrammetric method of DTM generation are small.

An international seminar on "Automated Quality Control of Digital Terrain Models" was organized by the author at AAU (Höhle, 2005b). Seven participants presented their methods and delivered results using the same test material.

2.8 Updating of DTMs

An important requirement of DTM users is the actuality of the data. Changes in the landscape occur due to construction activities and due to erosion. The DTM has therefore to be updated. First of all, the changes have to be located and the DTM has thereafter to be updated in these areas.

The methodology of updating by photogrammetry has recently been investigated by the author (Höhle 2009b). In Denmark, every third year new imagery with GSD=20cm is available for the whole territory. In addition, images with GSD=10 cm are at disposal for urban areas at the same time interval. Such imagery is the basis for the updating of the DTM in the areas of change, of incompleteness and of errors. The steps to be carried out are again orientation of images, DTM generation, editing, and quality control. The old DTMs can be used as approximations when a new one is derived. In the cities the results of the two flights (GSD=10cm and GSD=20cm) can be merged.

The manual editing of the DTM can be done by advanced display systems (cf. Figure 12). Errors in the DTM can easily be detected by stereo vision. The obtained results (NMAD values) were 15 cm in the open land, 25 cm in the built-up area, and 41 cm in forested area. This merging of different images contributes to higher accuracy and reliability (Höhle 2009b).

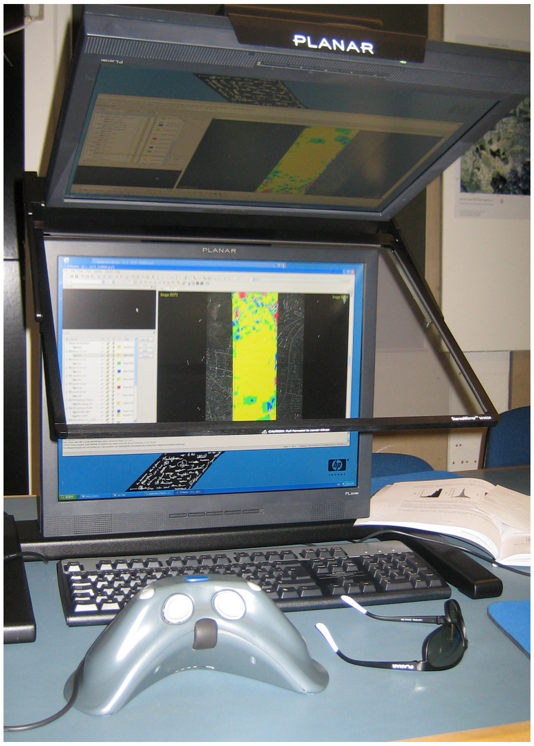


Figure 12.
Stereo display of Planar Systems, Inc. at the Laboratory of Photogrammetry at AAU. Calculated deviations from reference values are colour coded and superimposed onto the stereo model.

Taken from (Höhle 2009b)

Updating of DTMs is a continuous task. The use of the photogrammetric method in updating is economically and accurately.

2.9 Determination of the underwater terrain by photogrammetric methods

The DTM of land areas has to be seen in context with the DTM of the areas covered by water. A combined DTM with one reference system allows, for example, studies of flooding due to rise of water level. The photogrammetric determination of a DTM at shallow water areas has been a research project of the author for several years. After completion of his Doctoral thesis on the topic “Theory and practice of underwater photogrammetry” in 1971 new research was carried out. It dealt with the methodology of orientation of aerial photographs and with the instrumentation when underwater areas have to be mapped (Okamoto&Höhle 1972) and (Höhle 1972). Research in this field could later be continued in Denmark. Thanks to financial support of the Thomas B. Thrige’s Fond research work could be carried out at the Institute for Surveying and Photogrammetry on “Mapping of underwater terrain at sea shores and lakes” in 1985. The on-line derivation of the true depth by means of a modified analytical stereo-plotter was realized and tested with photographs of the Danish coast (cf. Figure 13). Results of these and other investigations were published in (Höhle 1988) and (Höhle 1990b).

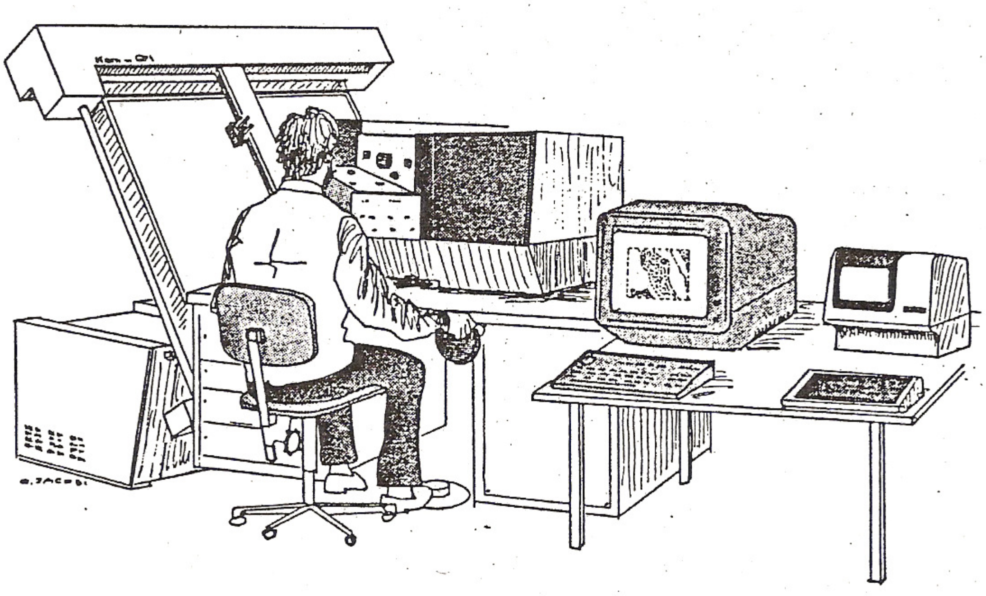


Figure 13. The analytical plotter with a graphical terminal is used by an operator to determine true water depth and contour lines in real-time.

Taken from (Höhle 1990b)

The achievable accuracy by photogrammetry depends on the transparency of the water body, the calmness of the water surface and of contrast on the sea bottom. The availability of digital cameras with high radiometric resolution will give better results in low-contrast areas of the sea bottom than with film-based images

The use of laser scanners with two types of lasers (using green **and** infrared light) is a solution in near-shore coastal waters. Detailed information on this technology is published in (Höhle 1987) and (Guenther 2007).

2.10 Data acquisition by Airborne Laser Scanning (ALS)

Airborne laser scanners determine the spatial position of small areas of the terrain (foot prints) by means of a laser beam. Monochromatic light is emitted from the laser and reflected from the surface of the terrain. The distance and the angle are measured. The obtained polar co-ordinates are converted into xyz co-ordinates of the scanner system. GPS- and INS-measurements are used to transform these relative co-ordinates into absolute co-ordinates of the reference system (e.g., the UTM system). This direct georeferencing of the scanner data requires the determination of the deviations between the different measuring devices (so-called “bore-sight alignment”). Figure 14 depicts the principle of ALS.

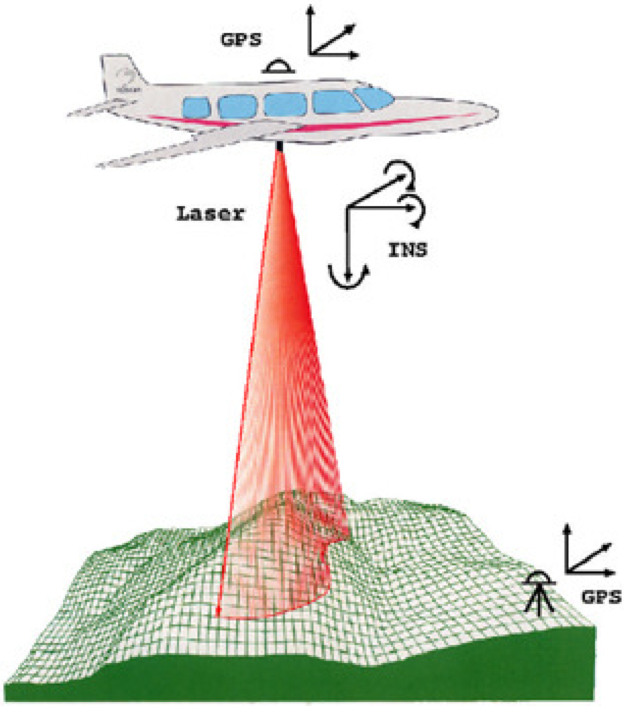


Figure14.
Principle of Airborne Laser Scanning. Polar co-ordinates (distance and angle) are determined by the scanner and GPS/INS measurements are used to determine the absolute position of the point cloud. The scan pattern in this type of scanner looks like a sinus wave. A regular grid of elevations is interpolated in post processing.

Taken from
TopoSys Topographische Systemdaten GmbH

The obtained point cloud has to be filtered for gross errors and then classified into off-terrain- and terrain points. A regular grid of elevations is interpolated afterwards.

Different types of laser scanners have been manufactured. The distance can be measured either by “pulse modulation” or by “continuous wave modulation”. The angle of the laser beam is measured by encoding the rotation of an oscillating mirror or at a “fibre-scanner” from the orientation of fibres, which transmit the laser pulses and receive the echoes.
Laser light can penetrate vegetation which is enabled by a relative narrow field of view (FOV) of the scanner and the fact that the measurements are carried out only from one position. Data acquisition can also take place at night.

The vertical accuracy of laser scanning can be high. In flat areas with good reflection the standard deviation of an elevation can be about 10cm. Areas with slope or vegetation are determined less accurately. The completeness may be a problem in areas of water and at objects of black colour (e.g. at roofs of houses or roads with asphalt). Figure 15 shows an example where houses with black roofs do not have footprints.

Prerequisite for a high accuracy is the calibration of the system (e.g., the bore-sight alignment). Also the condition of the atmosphere (rain, snow, refraction) and reflection near buildings (multipath) may influence the accuracy. Errors may also be introduced in post processing (classification and interpolation).

Figure 15. Laser scanning in built-up areas. The footprints are displayed inside buildings by red or green colour. Some of the buildings have none or only a few footprints because black roofs do not return the laser light. A DSM cannot be determined for such houses.

The checking of vertical accuracy is carried out as it is described in section 2.7. It is necessary to determine the planimetric accuracy in laser scanning.

The Figure 16 shows the **methodology for the determination of planimetric errors** carried out in (Höhle&Potuckova 2006). Houses are used to detect deviations at roof corners. The house corners are measured by an operator in a stereo-workstation and are then compared with the corners derived from the laser points (footprints) by adjustment of lines and intersecting them. Well defined points are the roof points of hip houses.

They can be determined from the laser points by derivation of planes and by intersecting them. Some roofs may also have chimneys and other objects above the planes. Such measurements have to be eliminated by a threshold for the residuals or by using robust adjustment. In the last approach big residuals are down-weighted by a function.

The investigation in (Höhle&Potuckova 2006) revealed planimetric errors in the tested laser scanning data of σ_p=1.0m at roof corners and σ_p=0.65m at roof points of hip houses.

The superimposition of map data and laser scanning data will show points within the building polygons which the filtering has not removed (cf. right image in figure16). Such points will make the DTM erroneous and have to be eliminated.

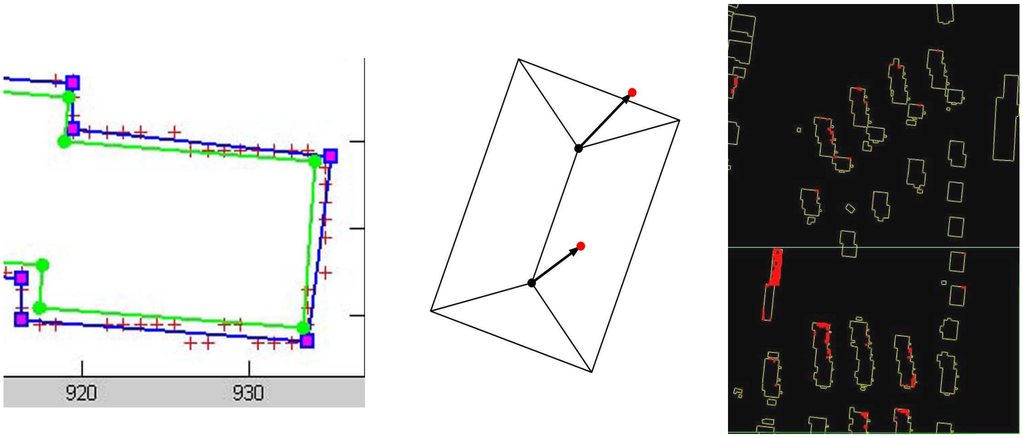


Figure 16. Planimetric errors of laser scanning data when comparing with a vector map. Errors of roof corners (left image), errors of roof points at hip houses (middle image), and blunders within houses (right image).

Taken from (Höhle&Potuckova 2006)

Laser scanning was recently used to determine a new DTM of Denmark. The technology is still in development and new hardware and software has recently been announced. The state of the art is summarized in (Mallet & Bretar 2009).

The problems of quality control of Digital Terrain Models derived by different methods were dealt with in an international seminar (Höhle 2005b) and in various projects (Höhle&Potuckova 2006), (Höhle 2009b).

2.11 Formats for DTMs

The storage and transfer of DTMs requires also formatting of the data. There are many standards established for elevation data. Basics on standards for raster data are published in (Höhle&Damgaard-Iversen 1994). Viewers and application programs can read different DTM standards. Very common for gridded DEMs are the ESRI Float Grid or the Danish DSFL format, for mass points and TINs the ASCII x/y/z or the binary file format .LAS, and for vector data the ESRI Shape file .SHP or the Danish DSFL format with the extension .dsf. DTMs for large areas are stored in tiles. Their size is limited to the area, e.g. 1km x 1km, or to the number of bytes (e.g. one GB).

3. Applications of DTMs

The applications of the DTM are multiple. Main applications are derivations of contour lines, production of orthoimages, mapping from single images, design of traffic ways, generation of 3D city models, simulation of sea level rise scenarios. These and other applications are dealt with in (Li et al. 2005) and (Maune 2007). In the following only those applications are described where the author contributed with development and research work.

3.1 Production of orthoimages

Orthophotos have been produced for many years. It is the fastest way to produce a map. A DTM is required in order to transfer the aerial image to one image of unique scale.

From 1971 to 1984, the author participated in the development of orthophoto instrumentation at the Wild Heerbrugg Company in Switzerland (today Leica Geosystems AG). In the seventies advanced instruments like A8/PPO-8 and OR-1 were developed and introduced into practice. The DTM was measured by an operator by means of profiles. He or she had to keep the measuring mark on the terrain when the motorized stereo instrument moved back and forth. The orthophoto was produced on film. Contour lines were computed from profiles and plotted or scribed and then copied together with the orthophotos. This product, orthophoto with contour lines, was an important breakthrough in mapping because such maps could be produced very economically and with a high quality (Höhle&Schneider 1973), (Höhle & Stewardson1977), and (Höhle 1983).

The availability of precision film scanners opened the possibility to produce orthoimages by means of computers. This possibility got the author's attention and he started research with the generation of digital orthoimages at Aalborg University in 1990. First experiences with the production of digital orthophotos were published in (Höhle 1992a).

Experiences with the production of digital orthophotos were also presented in (Höhle 1996a, **A9**). At that time, the computers at disposal had a relatively small memory (48 MB RAM) which caused long computing times. The influence of various factors (pixel size, DTM type, and resampling method) on the computation time and the quality of the orthophotos were therefore investigated by the author. The used DTMs had a relatively large spacing between the posts of the grid (20-50m) in order to keep the times for data collection and for computing of orthoimages low. The planimetric errors in the orthophoto could be reduced when break lines in the terrain were collected additionally. The results of this work were important for practice because digital orthoimages were produced for large areas and renewed in short intervals of time. In Denmark, for example, the DDO series have been produced in intervals of two years by COWI A/S since 1995.

The author's paper "Experiences with the production of digital orthophotos" received the 'John I. Davidson Award' of the American Society of Photogrammetry and Remote Sensing in 1997.

New applications of the digital orthoimages were presented in (Höhle 1990) and (Höhle 1991). The orthoimage became the base layer in a Geographic Information System (GIS) and source of thematic maps.

The event of the digital large format cameras in the year 2000 opened up for a complete digital production and an automation of the process. The contribution "Towards the Full Automatic Production of Orthoimages" in (Höhle & Potuckova 2001b) revealed the potential for a fully automated production of orthoimages.

The accuracy assessment of orthoimages was also a topic which was investigated in this context. Time-invariant objects like road crosses in an old orthoimage can be matched with a patch of a new orthoimage that contains the same object. The position of such objects is available from topographic databases. This process can occur automatically. **Details are described in "Automated Quality Control for Orthoimages and DEMs"** (Höhle&Potuckova 2005a, **A5**).

Orthoimages, which do not have displacements at houses and other elevated objects are called 'true' orthoimages. They are produced for the down town areas. The derivation of 'true orthoimages' first requires the detection of occluded areas and thereafter the filling of these areas with the content of other images. 3D models of houses including precise vector data for the roofs and imagery with large side lap (for example 60%) are necessary. Furthermore, invisible seam lines have automatically be created when the various image parts are fused together.

Dissemination of knowledge about the specification and use of orthoimages was done by means of a guide, which a working group of the "Geoforum" (Danish organization for mapping and GIS) published (Geoforum 2004/2005). The third version is currently in preparation. The author contributed with his knowledge to all versions of this user guide.

3.2 Slope and erosivity maps

The basis of this application is the **object-oriented DTM**. Such a DTM is used in Geographic Information Systems. Objects of the DTM are spot elevations; break and drain lines, obscured areas, etc (cf. Figure 3). These are data extracted from vector maps. All objects have attributes and the data are topologically structured. The objects and their attributes can be analyzed. For example, the elevations of a drain line should continuously become lower or higher. This fact can be used to find errors in the DTM.

More important is the possibility of generating new objects. One important derivate of DTMs are zones of equal slope (cf. Figure 17). If such slope data are overlapped with soil data, a soil erosivity map can be obtained. Areas with the same risk for land slide can be calculated and displayed. The potential of the object-oriented DTM was investigated in (Höhle 1992b) and (Höhle 1993a/b).

Figure 17. Contour lines and slope areas. The slope area in the range of 0°-2° is highlighted.

Taken from (Höhle 1993a)

3.3 Monoplotting with oblique images

The event of dense and accurate DTMs allows the mapping from single images. This monoplotting has been known for many years. The availability of georeferenced oblique images gives the possibility of deriving object dimensions from simple measurements on a computer screen.

Oblique images are well received by users because they give insight onto facades of houses. Other vertical objects like towers and electric poles can easily be recognized and also be mapped. The imaging ray is reconstructed and intersects the DTM facet (cf. Figure 18). The spatial position of the point of interest is then calculated.

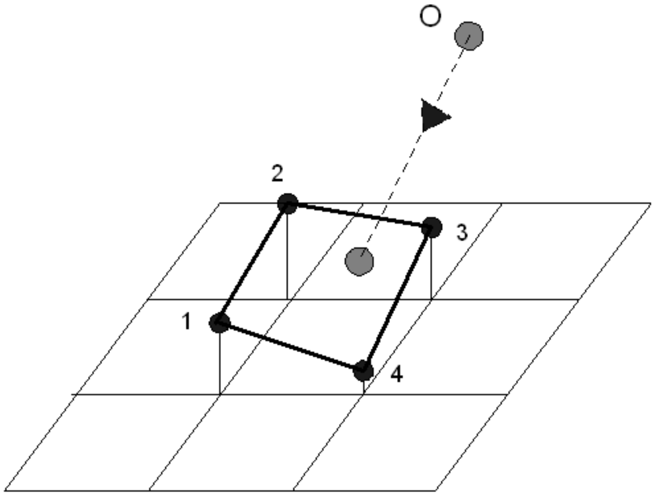


Figure 18.
Intersection of the image ray with the DTM facet

Taken from (Höhle 2008a)

In the publication **"Photogrammetric measurement in oblique aerial images"** (Höhle 2008a, **A3**) a commercial system was evaluated. Terrain elevations could be determined with an accuracy of RMSE=0.3m using a DTM derived from laser scanning and processed to a 10m x 10m grid. The heights of buildings could be determined with an accuracy of RMSE=0.6 m. The combination of a single image and a DTM gives the possibility to determine the spatial distance of a route.

3.4 Photo-realistic 3D landscape models

The orthoimage and the DTM can be used for the generation of a photo-realistic perspective view of the landscape. The first step drapes the orthoimage onto the DTM. In a second step a perspective centre, a viewing direction, and a viewing cone are selected and the photo-realistic view of the landscape is generated. Planned construction work can also be placed into this photo-realistic model of the landscape. The methodology is explained in (Höhle&Mikkelsen 1996). By mean of such images the planned construction can be evaluated by planners, politicians, and citizens (cf. Figure 19).

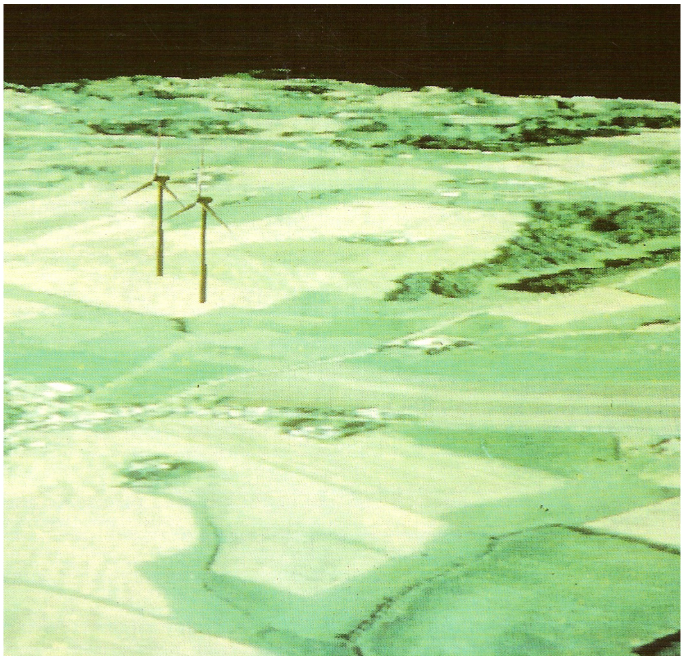


Figure 19.
Photo-realistic view of the landscape with planned windmills

Taken from (Höhle&Mikkelsen 1996)

3.5 Modelling of buildings and cities

The generation of 3D models of buildings and whole cities is currently a big task for photogrammetric companies and other organizations. For several large cities in Europe complete 3D models already exist, for example Copenhagen, Munich and Geneva. Such 3D models are demanded by the telecommunication industry which wants to position antennae onto houses and towers and thereby providing coverage of electromagnetic signals for cell phone communication. Another application of 3D city models is planning of new construction work like buildings, highways, etc. The presentation of a new design to the public may be done by a virtual 'walk through' or 'fly over' using 3D viewers.

For the production of such a 3D city models a Digital Terrain Model is necessary. Together with vector data of buildings the 3D city model can be created. The terrain elevations are needed because the topographic databases contain the peripheral lines of the roofs only. These lines are used to construct vertical walls by projecting them down to the terrain. A wire frame model can be created. In its simplest form it can consist of simple blocks. The roofs can be modelled with some standard forms (e.g. saddle roof and gable-window) or with all of the existing break lines.

The texturing of the 3D city models may be done by means of images which are taken from the air and from the ground. The models are then 'photo-realistic' consisting of vector and raster data. The images have to be rectified using three or four points which are determined by means of an image triangulation. A lot of manual work is involved.

In order to transfer the model into a dynamic model, which can be navigated, it has to be transferred into another language, for example VRML or X3D. More detailed information on the methodology and the description of examples can be found in **"On the Production of Photo-realistic and Dynamic 3D-Models of Building Structures by Means of Digital Photogrammetry"** (**A7**, Höhle 1998b). Other work regarding this topic is published in (Höhle 1995), (Höhle 1996c), (Höhle 1997), (Höhle&Pomaska 2000a/b).

Figure 20 shows a photorealistic 3D model of a church, which was produced by students of the University of Applied Sciences Bielefeld, when they participated in an exchange program with students of Aalborg University.

Figure 20. Photorealistic 3D model of a church in Aalborg with additional rendering

Taken from (Luhmann et al. 2006)

The 3D city models may be connected to databases which enable access to other information about the buildings. Such a task was solved by V. Kralova, CTU in Prague, in her dissertation (Kralova 2008), (Höhle et al. 2008b).

Another approach is to produce a very dense point cloud by photogrammetry and from there derive a Digital Surface Model (DSM). The texture is then projected onto the DSM using georeferenced images. In this way the generation of photo-realistic 3D city models can be automated to a great extend. The state of the art in this approach is published in (El-Hakim 2008).

3.6 Navigation and fishing maps in coastal areas

Coastal areas are regions of dynamic changes. The underwater terrain, the coast line and the installations for the protection of coasts have to be surveyed and monitored. Ships have to rely on the underwater DTM in order to avoid touching the sea bottom or underwater installations. The safety of the ship traffic is of concern to the state organizations dealing with hydrographic surveying and mapping. The navigators of the large vessels have to be informed about the current status of the underwater DTM and of obstacles in their routes. Depths and important objects on the sea bottom (wrecks, rocks, pipelines, etc.) are contained in "Electronic Nautical Charts".

The need for safe navigation is also valid for fishermen and their small fishing boats. In addition to depth information, they like to have other information in large-scale maps. They continuously update this digital map with the position of their latest catches and of features on the sea bottom where fish may hide. The production of equipment for positioning, depth measurement and mapping of sea bottom features is also an industry, for example in Denmark.

Other applications of the underwater DTM are planning of constructions like pipelines, bridges, tunnels and windmills. After construction of such objects it is necessary to monitor and maintain these installations.

These and other examples are described in more detail in **"Application of Terrain Modelling in Coastal Areas"** (Höhle 1987, **A10**).

The transition zone between land and sea is very important and needs the attention of surveyors, photogrammetrists and hydrographers. There are currently joint efforts in creating databases for such areas in the same reference system (EuroSDR 2007).

4. Some economic considerations

The cost is very important when a method for acquisition or processing has to be selected. Factors which influence the cost are the required accuracy, the type of terrain, the shape of the area, the instrumentation (sensor and software packages) and personnel to be used. The last one is now becoming decisive and today companies organize joint ventures with organizations in low-paid regions of the world.

A relation between cost and accuracy of different acquisition systems is published in (Mercer&Schnick 1999). Only aerial photography and airborne laser scanner can deliver highly accurate and dense data. Interferometric Radar and satellite-based systems produce medium or low accuracy elevation data only. The unit price is then much lower for these systems (cf. Figure 21).

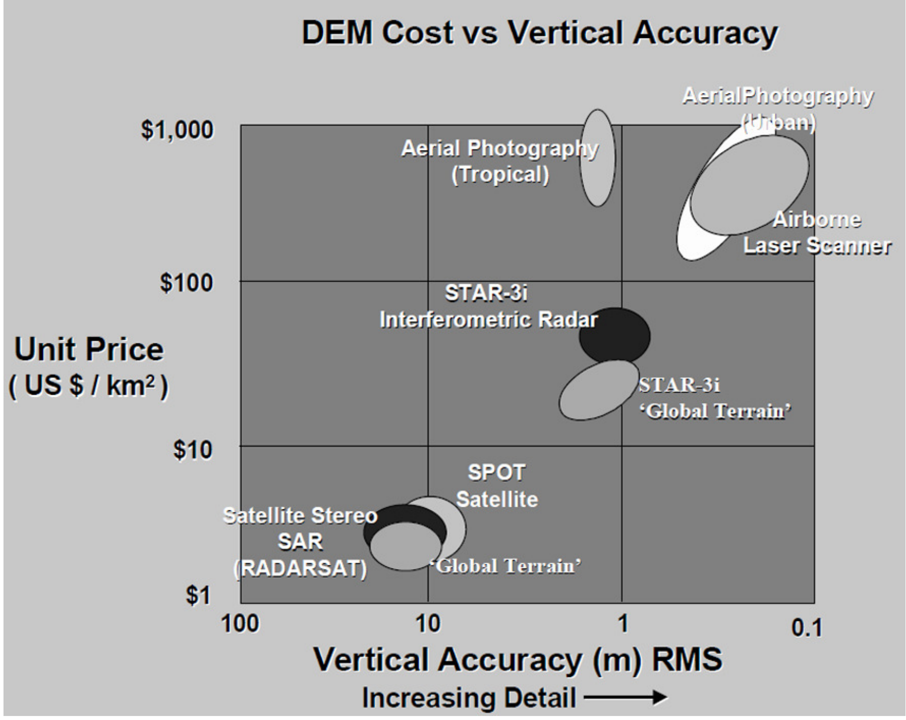


Figure 21. DEM cost and vertical accuracy for different sensors

Taken from (Mercer&Schnick 1999)

In the following the **cost of digital aerial photography** is discussed. The efforts for each single step of the production should be known in order to know where technical improvements will be most effective.

The time consumption when using photogrammetry in the DTM production is, after experiences in (Höhle 2008), about the following:

1. Preparation (adaptation and checking of orientation data, generation of image pyramids, selection of checkpoints and of other reference data): 30 minutes per image.

2. DTM generation (selection and input of DTM parameter and of morphological data, calculation, verification of results): 110 minutes per image.

3. Automated editing (selection and input of filter parameter, filtering, filling of gaps): 25 minutes per image.

4. Manual editing (viewing of DTM-tiles as contour lines, profiles, perspectives, and by stereo-vision, removal of blunders, brush filtering, shifting of Z-reference, closing of gaps, conversion to another format): 330 minutes per image or 4 hours per km^2 using 20cm imagery.

5. Assessment of accuracy (calculation of standard and robust accuracy measures, documentation of errors in metadata): Approximate 10 minutes per image.

A block of 12 images (three strips with four images each) with GSD= 20cm (covering about $16.3km^2$ at 60% forward overlap and 20% side overlap) could then be done in approximate 101 hours. This performance of about 6.2 hours/km^2 may be different for other circumstances. The given times can be converted into cost when using salaries of the workforce, cost of acquiring instrumentation, and adding cost for amortization and overhead, etc. Details on such cost calculations for mapping projects can also be found in (Höhle & Pohjola 1983).

The efforts for manual editing of DTMs in built-up terrain and forested areas are high; they may be reduced when the automatic editing would perform more reliably. When using photogrammetry the images can be used for many purposes, for example for the orthoimage production, stereo-compilation for updating the topographic databases, DTM quality control, etc. This universal use of imagery is also an economic factor.

5. User requirements to DTMs

The described applications indicate that DTMs can have different characteristics and contents. The elevation data can be structured as uniformly-spaced grid or triangles of different form and size (TIN). The DTM may have to be supplemented with other data in order to satisfy the requirements of the intended application. One necessary addition is metadata. They should contain the date of acquisition, the make of the sensor, the flying height, the datum and projection for the used reference system, the horizontal and vertical accuracy, the border lines of no data areas, etc. In Table 3 the requirements for a few applications are listed.

application	requirements
contour lines of topographic maps (contour interval=0.5m)	DTM (0.15), TIN spot elevations, break lines
production of orthophotos with GSD=0.4m	DTM (1.75), grid bridges (polygons, mass point elevations)
production of true orthophotos with GSD≈0.1m	DTM (0.15), grid wire-frame 3D city model
slope and erosivity maps	DTM (0.15m), grid
measuring from single images	DTM (0.3), grid
photo-realistic 3D landscape models	DTM (0.5), grid with high density
3D city models	DTM (0.15), TIN
Electronic Nautical Charts	DTM (0.3), grid objects above sea bottom, coast line
hydrologic modelling	DTM (0.2), TIN break lines, shore lines, dikes, culverts, buildings

Table 3. Requirements of various applications. The value in parentheses for DTM is the required accuracy (RMSE) in meter.

For the **generation of contour lines** with a 0.5m interval a high accuracy demand exists, about 1/3 of the contour interval. In order to generate contour lines of high cartographic quality it may be necessary to add break lines. The elevation data are best structured as TIN. Spot elevations on important features like road crossings and local extremes (top of hills and bottom of valleys) are also features of topographic maps.

The **production of orthophotos** mostly uses gridded DTMs. Their accuracy can be medium. In (Geoforum 2004/2005) it is recommended that orthoimages with a ground sampling distance of GSD=0.4m, produced from images taken by large format frame cameras, should have a RMSE less than 1.75m. This also means that the orthoimage can be derived from DTMs with relatively wide grid spacing. Such DTMs of low resolution allow processing in small workstations and the produced orthoimages will have fewer artefacts. The ortho-rectification of elevated objects such as bridges, overpasses, etc. requires special attention. Polygons with the edges of these objects and mass point elevations contained in the polygons have to be processed so that the objects are imaged at the correct position.

The **production of true orthophotos** uses images of high resolution (GSD≈10cm). A wire-frame 3D city model is a prerequisite. The DTM accuracy has therefore to be compatible with the vector data of the topographic database (RMSE=0.15m).

Slope and erosivity maps require a similar DTM accuracy as 0.5m contour lines (RMSE=0.15m). The elevation data are best structured as a uniformly-spaced grid. This high demand is for open terrain. In areas with vegetation (forests) the demands are lower.

The **measuring from single images** (monoplotting) requires a DTM in order to determine the 3D co-ordinates, distances, areas and heights of buildings. Especially oblique images are used. Such non-metric imagery is georeferenced and of medium or small formats. The accuracy of the orientation is therefore not very high and the DTM may be of medium accuracy or with a relatively wide spacing of the grid posts.

The **photo-realistic 3D landscape model** requires a DTM of medium vertical accuracy (about RMSE=0.5m). The cell size of the DTM should be of the same size as the pixel of the orthoimage so it can easily be draped onto the DTM. The cell size of the DTM should therefore be small in order to have a good image quality (resolution) on the photorealistic model. The DTM may have to be densified and this increase of data will slow down the processing of a new perspective. Dynamic photorealistic models of the landscape will use a TIN structure with large triangles. The photo texture is then projected onto the triangles of the DTM.

The requirements for DTMs to be used in the generation of high-quality **3D city models** are a high geometric accuracy (RMSE=0.15m). A big systematic shift in the reference of the DTM (mean error) will lead to wrong heights of the building which is derived as the difference between the DTM and the elevations of the roof. The density of the DTM should also be high in order to avoid errors in building heights, especially in hilly terrain. 3D city models of the future will be object-oriented. The upcoming standard is "City GML". It requires that the DTM, which is part of the 3D city model, has to be structured with objects too.

To the navigator of a vessel the DTMs of **Electronic Nautical Charts** (ENCs) have to be displayed as depth values taking the current water level into account. There is a demand that the charts of the international routes are updated weekly and accurately (RMSE=0.3m). The depth values of the ENC refer to the Mean Lower Low Water (MLLW). Also obstacles on the bottom of the sea (e.g. shipwrecks, rocks, pipelines, etc.) and on the water surface (e.g. bridges, vindmills, buoys) have to be contained in the ENCs.

The simulation of floods is one important application of terrain models. After regulations of the EU maps for risks of flooding have to be produced in each of the member countries. DTMs are used in order to simulate the rise of the sea, heavy rainfalls or storms. Such a terrain model must include break lines, shore lines, ditch centre lines, dikes, etc. The elevation data are organized with advantage in triangles (TIN). Buildings have to be included in the **hydrologic modelling** because they also affect the flow of water. The shore line of lakes should have one elevation only while the shore line of rivers must have decreasing elevations. There must be a common vertical datum for sea and land. All these requirements may lead to a special DTM which can be derived from the national DTM by adding some features from other sources. The accuracy of the DTM to be used for hydrologic modelling has to be rather high (RMSE=0.2m).

6. Answers to current problem areas of DTMs

Mapping organizations are confronted with some problem areas regarding DTMs today. They can be formulated as four questions:

What are the requirements of DTM applications?

What is the proper method in the updating of DTMs?

What are the procedures in photogrammetric DTM generation?

What kind of quality control is required?

In the following the answers to the questions will be given one by one. They are based on the experiences of the author and the investigations in this contribution. Special conditions in mapping organizations may come to other answers. The suggested solutions to the current problems are, therefore, not complete and not valid for all cases.

What are the requirements of DTM applications?

In the previous chapter the demands for some applications are documented. It can be seen from Table 3 that the required accuracy in these applications differs from 0.15m to 1.75m. The establishing of a nationwide DTM of high accuracy and high density is therefore a good solution. From this basic DTM new DTMs of lower accuracy and density can be derived in order to speed up the processing at a certain application. A wider spacing of the grid posts leads automatically to a reduced accuracy. It depends on the terrain which spacing of the grid posts can be applied. The proper spacing can be derived when knowledge about the terrain is available. Investigations of O. Jacobi have derived a relation between the spacing of the grid posts and the DTM error for various terrain types by means of an effect spectrum (Jacobi 1994).

$$\sigma^2 = 1.9 \cdot 10^{-4} \cdot (\Delta X)^{1.5} \text{ (Danish moraine landscape)}$$

$$\sigma^2 = 3.0 \cdot 10^{-3} \cdot (\Delta X)^{1.7} \text{ (Mountainous terrain)}$$

The required DTM error can then be calculated from the error at the DTM post and contribution of the terrain by

$$\sigma_R = \sqrt{\sigma^2 + \sigma_{Post}^2}$$

Figure 22 depicts this relationship. If an application, for example, requires a DTM of an accuracy of σ_R=0.5m, then a spacing of the grid posts of 117m would be sufficient for the Danish moraine landscape. A standard deviation of σ_{Post}=0.1m at the single posts is assumed in this example. At mountainous terrain, however, the spacing of the grid posts should not exceed 13m in order to obtain the same DTM accuracy of σ_R=0.5m.

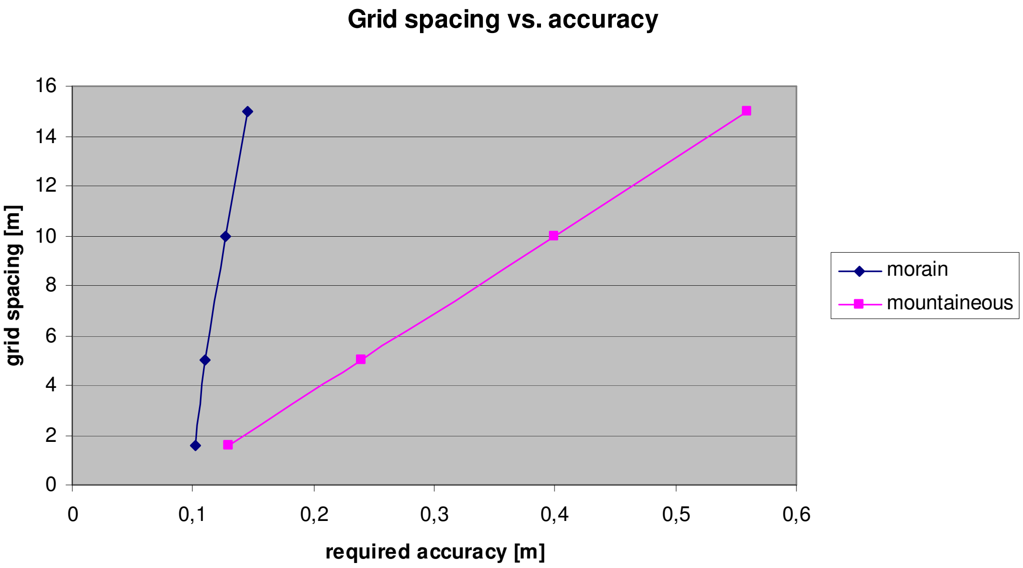


Figure 22. Spacing of the DTM grid points as function of the required accuracy (σ_R) and the terrain type. An error of the DTM post is assumed with σ_{Post}=0.1m.

The original DTM may therefore be stored in various resolutions as levels of a DTM pyramid. In some applications new information has to be added in order to make the DTM “fit for purpose”. Each cell of the DTM can also have other attributes beside the elevation, for example slope and aspect. This is the concept of the object-oriented DTM. Other objects are break lines, spot elevations and local extremes.

Additional layers of information can also be added. They may contain the data of bridges and overpasses necessary for the production of orthoimages. Small objects like dikes, walls, ditches have to be added when floods have to be simulated in order to produce flood insurance rate maps. This requires either a very high density of the DTM or additional vector data.

From these and other applications it is obvious that elevation data alone are not enough to solve all of the tasks. Many of the additional features (e.g. break lines, 3D building models) can be taken from images.

What is the proper method in updating of DTMs?

DTMs can be produced by different methods. Laser scanning was recently used for the generation of DTMs for large areas. It is mainly the possibility to measure to the terrain in areas with vegetation that makes laser scanning attractive. The measurement is done from one position only and the laser beam penetrates to the ground if the vegetation is not too dense. Photogrammetry needs at least two images to derive elevations. The imaging rays have a rather big inclination which makes measurements in forests difficult or impossible. The wide-angle photography allows for large coverage and requires therefore less flying. Its accuracy depends on the flying height.

Actuality of the data is important for most of the applications. The updating has to be done only for those areas where changes in the terrain occurred. It will be relatively small areas which have to be measured. Nation-wide photography is done in short intervals and used for updating of vector data and renewal of the orthoimages. Images are therefore available at no cost. Recently, many new innovations became known for the photogrammetric methodology. Photogrammetry is a universal method which combines the mapping of planimetric features like break lines, dikes, ditches, etc. with the mapping of elevations. High accuracy in elevations **and** planimetry is achieved. The density of the original data can be extremely high. For each pixel an elevation can be generated, for example 121 elevations per m^2 for images with GSD=10cm. In the investigations of the author accuracies were achieved which approach these from laser scanning. Recently published results achieve similar or even better results when using images of higher overlap (Haala&Wolff 2009). Certain prerequisites have to be fulfilled in order to achieve optimal results by photogrammetry.

There are advantages and disadvantages for both methods, it would be best to combine photogrammetry with laser scanning. Whether such a combined use is cost-effective has to be proved when hardware and software is developed. In the meantime both methods will exist side by side. Photogrammetry can meet the requirements of the majority of applications.

What are the procedures in photogrammetric DTM generation?

Photography should be taken with digital large format cameras at a time where no leaves are on the trees. The flying height has to be adapted to the accuracy demand and the applied camera. For example, when using the DMC camera, a flying height of 845m would achieve a standard deviation of σ_h=10cm for the automatically derived elevations. The GSD of the images is then 8.5 cm.

If the GSD is given then the achievable vertical accuracy can be determined for large format frame cameras and stereo-pairs with 60% forward overlap by:

$$\sigma_h = K_{cam} \cdot \sigma_{px'} \cdot GSD \qquad (4)$$

$$K_{cam} = \frac{c}{0.4 \cdot s'_{fld} \cdot pel'}$$

where

c… camera constant, [mm]
s'_{fld}… image size in flight direction, [mm]
pel'… pixel size, [µm]
K_{cam} … camera parameter (60% overlap), [μm^{-1}]
$\sigma_{px'}$ … parallax accuracy, [µm]
GSD… Ground Sampling Distance, [cm]
σ_h … vertical accuracy, [cm]

The formula (4) is the same as in (1), but uses the terms GSD and K_{cam}, which are characteristically for digital photogrammetry.

A practical **example** is given in the following. The parameter K_{cam} for the digital large format frame camera DMC acquiring images with 60% overlap is 0.27 [μm^{-1}]. The parallax accuracy (standard deviation) was in practical experiments determined with $\sigma_{px'}$ =4.4µm (Höhle 2009). Using images with GSD =10cm can therefore achieve a vertical accuracy (standard deviation) of σ_h=12cm in open terrain. According to formula (2) the flying height has to be h=1000m in this example.

-Orientation of aerial images

Accurate orientation of the sensor is the first prerequisite for good DTM results. The integrated sensor orientation should be applied because the intersection of multiple rays makes a block of images very stable. The tie points, which connect the images of a block, can be found and measured automatically. Such an automated triangulation enables a high accuracy and reliable results. Here, photogrammetry definitely has an advantage in comparison with airborne laser scanning. A few control points on the ground are still necessary. Data bases with time-invariant features like house roofs, manhole covers, drain gratings, etc. allow a fully automatic approach.

-Generation of point clouds

The automatic generation of points clouds and gridded DEMs can now use improved tools, for example the software package Match-T, version 5.2. Multiple images (instead of single stereo-pairs) are processed so that seamless DEMs are generated whereby each elevation is determined by several image rays. The spacing of the posts can be as little as one GSD. Terrain specific parameters can be used when areas of a certain terrain type are separately processed. The areas of houses may be excluded from the DEM calculation when vector data of the houses are at disposal. Break lines can be added and will improve the results.

-Filtering and classification

The filtering automatically eliminates gross errors and elevation above ground. Additional manual editing by means of stereo vision is effective and, therefore, recommended. The result is a DEM with some gaps.

-Completion of DTMs

The filtering will produce gaps in the data. They have to be filled by interpolation with the remaining points. The gap distance shall not be too big otherwise errors will be created at undulating terrain.

-Supplementing with other data

Stereo measurements of single elevations can be carried out in order to complete the DTM or reduce the gap distances. Other data have to be supplemented in order to make the DTM 'fit for purpose', that means the DTM has to be adapted to a special application. This can also be a thinning of the DTM.

What kind of quality control is required?

The quality control should already start within the production process. The single steps of the production process should have their own quality control. In this way it is ensured that the required quality of the final DTM can be achieved. One of the checks can be that there are no points of elevated objects (houses, areas with trees, etc.) within their polygons. Other checks are for shore lines and drain lines which should have either a constant elevation or continuously decreasing elevations. Visual checks of the contour lines superimposed onto the stereo-pairs are very effective to detect blunders.

The quality control of the final DTM has to be carried out by means of check points of superior accuracy. They should be distributed over the whole DTM area and be available for each of the terrain types. At least three terrain types should be selected: Open terrain, built-up area, and forested area. The number of check points per terrain type should at least be 20 if the distribution of the deviations to the reference values is normal. The standard quality measures (RMSE, mean, and standard deviation) are computed. The non-normal distribution of deviations to the reference values requires robust accuracy measures such as median and the 68.3% quantile.

These values are not influenced by gross errors and/or a skew distribution of the errors. For applications like road construction, flooding risks, etc. it is important that the systematic shift in the elevation (mean) is reliably determined. The test algorithm is depicted in the Figure 23. Histograms or Quantile-Quantile- (Q-Q)-plots give an answer if the distribution of errors is normal. It is a visual check. Another criterion for the non-normality of the error distribution is the size of the deviation between the 'Mean' and the 'Median' or between the standard deviation and the NMAD value. In this way the decision can be automated. Robust accuracy measures have to be calculated and used in the case of non-normality. Confidence intervals show the limits in which the estimated values will be located with a 95% probability.

The efforts for ground measurements of check points are high. Checking of extensive areas has to use more economic but nevertheless accurate methods for the quality control of DTMs. The method of automatic measurement of parallaxes between corresponding image parts of two overlapping orthoimages, can be the answer.

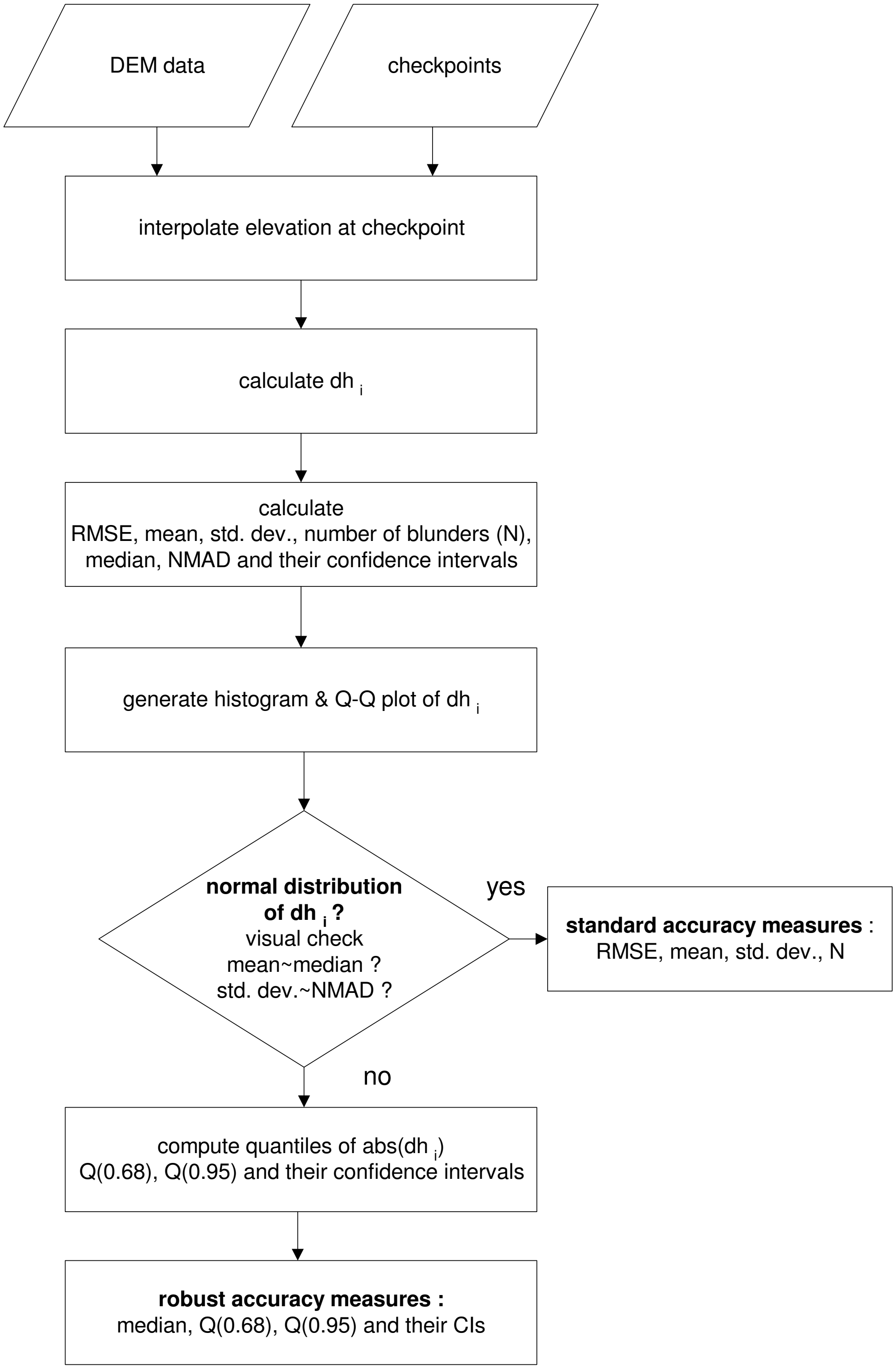


Figure 23. Test algorithm for the determination of DTM accuracy measures

7. Conclusion

From the previous chapters it can be concluded that generation and application of DEMs have had a tremendous development over the years. The changes in technology and user demands will also occur in future. New applications will arise. The competitive situation between companies will make the product cheaper.

A universal demand is the actuality of the data. Especially the updating of the DTM is an important task. Investigating the various applications made it clear that a DTM with a fixed and narrow spacing between grid posts cannot meet the demands of all the different applications. Computation times may become too long in smaller computers. Thinning of the data can overcome this problem when the accuracy requirement is not so high. DTM pyramids with levels of different resolution may be created.

In some applications special features and additions are required. For example, local extremes and break lines are necessary for the generation of high-quality contour lines. Hydrological studies require a higher DTM accuracy than the studies for mobile telecommunication. The coastal zones require DTMs with **one** vertical datum, map projection and shore line when the task is to plan constructions, simulate floods or define borders. The DTM to be used in a certain application has to be ‘fit for purpose’ and special editions of the DTM are necessary.

Regarding the measuring method for DTM generation, several methods are available. Laser scanning and photogrammetry are used when high accuracy is demanded. Technical arguments like the required accuracy, density and completeness decide which method should be used in a particular terrain type. Cost becomes an issue if the technical demands can be fulfilled. Laser scanning has an advantage in forested areas. Photogrammetry is attractive when imagery exists or can be used for other tasks such as orthoimage production and stereo-compilation of topographic maps. The user requirements in various applications revealed that additional information is necessary in order to carry out an application. For example, narrow dikes and walls are important for hydrologic modelling and should be ‘visible’ in the DTM. The spacing between grid posts must then be very narrow or break lines have to be added. Regarding the planimetric accuracy, the photogrammetric method has an advantage because the images can be connected by means of automatically measured tie points. Laser scanning has fewer blunders in the elevations. The automatic detection and removal of blunders has to be improved in both methods in order to increase the reliability of the DTM data.

Checking the DTM quality has to be carried out in a few samples of different classes of terrain. Robust accuracy measures (together with confidence intervals) should be applied in order to find reliable values for the systematic vertical error (median) and the vertical accuracy (68.3% quantile) for each class of terrain. Planimetric accuracy should also be determined using lines and points of houses or other suitable objects.

Regarding the technology, the multiple-line camera (for example the ADS40 of Leica Geosystems) has potential for high DTM accuracy as well. In near shore waters the underwater DTM should be determined by more economic methods than the hydrographic method. Scanning with green and infra-red lasers or digital photogrammetry with GPS/IMU sensors are here new possibilities. Satellite-based cameras or scanners and airborne interferometric SAR can determine DEMs of lower accuracy but they are very economic and efficient. The price/performance relation will decide which DTM acquisition method should be selected.

This investigation mainly dealt with digital large format frame cameras, software for the automatic derivation of DTMs and hardware and software for editing of raw data. The photogrammetric approach in the generation of accurate and dense DTMs can meet the requirements in most of the DTM applications.

8. Abstract

From 1967 until 2009 the author has contributed to the research topic "Generation and application of Digital Elevation Models". His publications in scientific journals, conference proceedings, and research reports show the enormous progress in this field and document his contributions to this progress. His technical and scientific contributions reach from the development and tests of new instrument systems, developing of procedures in the quality control to the exploration of new applications of DTMs.

The generation of DTMs by means of photogrammetric methods is still an actual topic although other methods were developed. Airborne laser scanning, for example, was used for the new country-wide Digital Terrain Model of Denmark, but editing and updating of the DTM can successfully be done by means of digital photogrammetry. The combination of photogrammetry and laser scanning is an optimal solution for generation and updating of digital terrain models.

This thesis summarizes the author's results of research on the topic "Generation and application of Digital Elevation Models". It is divided into the various steps of the production and various applications. The author's contributions are explained by means of a short text, by important figures, and the title of the publication. 10 important articles and the list of his and other publications regarding the research topic "Generation and application of Digital Elevation Models" are attached. Two completed PhD theses on "Image Matching and its application in photogrammetry" and on "Automatic Generation of Elevation Data over Danish Landscape", were both initiated and guided by the author. Many of his 54 publications regarding DTMs (including 10 which are registered in the 'Web of Science') were published at an early date and in scientific journals with a relatively high impact factor.

The major contributions of the author to the field of knowledge "Generation and application of Digital Elevation Models" are the following:

- investigation of the procedures in the automated generation and editing of DTMs
- evaluation of the quality of DTMs applying new photogrammetric and statistical methods
- testing of new applications of DTMs: production of orthoimages and erosivity maps, visualization of the landscape, and mapping by means of single oblique images
- developing and testing a new method for the derivation of orientation parameters of aerial images by using existing DTMs, orthoimages and vector maps
- dissemination of knowledge on the new methods and procedures by means of interactive learning programs
- answers to the current problem areas regarding the generation and application of DTMs.

9. Sammendrag

Forfatteren har i perioden fra 1967 til 2009 bidraget til forskningsområdet ”Fremstilling og anvendelse af digitale højdemodeller”. Hans publikationer i videnskabelige tidsskrifter, konference ’proceedings’ og forskningsrapporter viser det enorme fremskridt på dette fagområde og dokumenterer hans bidrag til fremskridtet. Disse tekniske og videnskabelige bidrag rækker fra udvikling og tests af nye instrumentsystemer, udvikling af procedurer i kvalitetskontrol til afprøvning af nye anvendelser af DTM.

Fremstillingen af DTMs vha. fotogrammetriske metoder er stadigvæk et aktuelt emne, selvom andre metoder blev udviklet. Laserscanning fra fly, for eksempel, er anvendt til den nye landsdækkende DTM i Danmark, men editering og ajourføring kan succesrigt udføres ved hjælp af digital fotogrammetri. Kombination af fotogrammetri og laserscanning er en optimal løsning i fremstilling og ajourføring af digitale terræn modeller.

I denne forstående afhandling er flere af de opnåede forskningsresultater beskrevet mere detaljeret. De er inddelt i de forskellige trin i fremstillingsprocessen og i forskellige anvendelser. Forfatterens bidrag er forklaret ved hjælp af kort tekst, vigtige figurer og titlen af publikationen. 10 vigtige artikler og listen af hans og andres publikationer med hensyn til forskningsområdet ” Fremstilling og anvendelse af Digitale Højdemodeller” er vedlagt. To afsluttede PhD projekter, ”Image matching and its application in photogrammetry” og ”Automatic generation of elevation data over Danish landscape”, blev begge initialiseret og vejledt af forfatteren. Mange af hans 54 publikationer (inklusive 10 som er registreret i ’Web of Science’) vedrørende emnet er publiceret på et tidligt tidspunkt og i videnskabelige tidsskrifter med relativ høj ’impact factor’.

Forfatterens hovedbidrag til forskningsområdet ”Fremstilling og anvendelse af Digitale Højdemodeller” er følgende:

- undersøgelse af procedurer ved den automatiske fremstilling og editering af DTM samt formidling af erfaringer
- evaluering af kvaliteten af digitale terrænmodeller under anvendelse af nye fotogrammetriske og statistiske metoder
- tests af nye anvendelser af DTM: Produktion af ortofotos og jorderosionskort, visualisering af landskabet og kortlægning ved hjælp af enkelte skråfotos
- udvikling og tests af en ny metode for bestemmelse af orienteringsparametre af flybilleder ved hjælp af eksisterende DTM, ortofotos og vektorkort
- formidling af viden om nye metoder og procedurer vha. interaktive indlærings-programmer
- svar til aktuelle spørgsmål vedrørende fremstilling of anvendelse af DTM.

References

Publications of the author

(Articles marked with * are peer reviewed and are contained in 'Web of Science')

*Höhle, J., 2009a, DEM Generation using a digital large format frame camera, Photogrammetric Engineering & Remote Sensing, vol.75, no. 1, pp. 87-93

Höhle, J., 2009b, Updating of the Danish Elevation Model by means of photogrammetric methods, Technical report no. 3 of the 'National Survey and Cadastre-Denmark', ISBN 87-92107-25-7, pp. 63 (published at: http://www.kms.dk/NR/rdonlyres/1C10C559-6CC9-4520-85C5-DE8659CB38A9/0/kmsrep_3.pdf)

*Höhle, J., Höhle, M., 2009c, Accuracy assessment of Digital Elevation Models by means of robust statistical methods, ISPRS Journal of Photogrammetry and Remote Sensing, vol.64, issue 4, pp. 398-406

*Höhle, J., 2008a, Photogrammetric Measurements in Oblique Aerial Images, Photogrammetrie, Fernerkundung, Geoinformation, nr. 1, pp. 7-14

Höhle, J., Kralova, V., Pavelka, K., 2008b, Application of New Visualization Methods with Interactive Elements for Monument Preservation. In: CTU Reports : Proceedings of Workshop 2008, 2 p.

Höhle, J., 2007, The EuroSDR Project "Automated Checking and Improving of Digital Terrain Models", Proceedings of the Annual Conference of the American Society of Photogrammetry and Remote Sensing, Tampa, Florida, May 7-11, pp. 12

Höhle, J., Potuckova, M., 2006, The EuroSDR Test "Checking and Improving of Digital Terrain Models", in: EuroSDR Official Publication, No. 51, pp. 9-142

*Höhle, J., Potuckova, M., 2005a, Automated Quality Control for Orthoimages and DEMs, Photogrammetric Engineering & Remote Sensing, Vol. 71, No. 1, pp. 81-87

Höhle, J., 2005b, International Seminar "Automated Quality Control of Digital Terrain Models" at Aalborg University, Photogrammetrie, Fernerkundung, Geoinformation, nr. 7, pp. 565-568

Geoforum, 2004/2005, Vejledning/specifikation om ortofotos (Guide/specification on orthophotos), authored by Buch, S. ; Dueholm, K. ; Elgaard, S. ; Flatman, A. ; Hviid, C. ; **Höhle, J.** ; Jepsen, H. ; Jørgensen, L. T ; Laursen, V. W ; Madsen, P. S ; Sørensen, J. M, in: www.geoforum.dk : red. / Buch, S., 1. og 2. Edition, København: Geoforum Danmark, pp. 62

Höhle, J., 2003, Automatic Orientation of Aerial Images on Topographic Databases – an overview, in: Skriftserie Department of Development and Planning, nr. 287, pp. 3-16

Höhle, 2002, Automated Orientation of Aerial Images, Bildteknik/Image Science, nr. 1, pp. 91-101

Höhle, J., Potuckova, M., 2001a, Steps to Automated Orthoimage Production**,** Proceedings of the International Symposium "Geodetic, Photogrammetric and Satellite Technologies" : Development and Integrated Application, Sofia, Bulgaria

Höhle, J., Potuckova, M., 2001b, Towards the Full Automatic Production of Orthoimages**,** Photogrammetrie, Fernerkundung, Geoinformation, Vol. 6, pp. 397-404

Höhle, 2001, Automated Georeferencing of Aerial Images, Proceedings of the 8th Scandinavian Research Conference on Geographical Information Science (ScanGIS'2001), Ås, Norway, pp. 115-123

Höhle, J., Pomaska, G., 2000a, Bygningsmodeller - visualisering og dynamisk præsentation (Building models – visualization and dynamic presentation), in: Arkitekten, vol. 102, nr. 5, pp. 20-25

Höhle, J., Pomaska, G., 2000b, Zur Visualisierung von Gebäudemodellen und deren dynamische Präsentation im Internet (On the visualization of building models and their presentation on the Internet), in: Bauinformatik-Journal, vol. 1-2, pp. 55-63

Höhle, J., 1999a, Orientation of Aerial Images on Database Information, in: OEEPE Official publication nr. 36, pp. 71-117

Höhle, J., 1999b, Orientation of Aerial Images by Means of Existing Orthoimages and Height Models – Results from Experiments with OEEPE Test Material, in: OEEPE Official publication nr. 36, pp. 159-165

Höhle, J., 1998b, On the Production of Photorealistic and Dynamic 3D-Models of Building Structures by Means of Digital Photogrammetry, in: Visual Reality : Proceedings of the International Conference on Multimedia in Geoinformation ("Visual Reality '98"), March 16-18, Bonn, Germany, KTH Högskoletryckeriet, Stockholm, Sweden, ISBN 91-630-6626-2, pp. 141-150

Höhle, 1998c, Automatic Orientation of Aerial Images by Means of Existing Orthoimages and Height Data, Proceedings of the ISPRS Commission II symposium, Cambridge, UK, pp. 121-126

Höhle, J., 1997a, The Automatic Measurement of Targets, Photogrammetrie, Fernerkundung, Geoinformation, nr. 1, pp. 13-21

Höhle, J., 1997b, Photorealistische und Dynamische 3D-Bauwerksmodelle (Photorealistic and Dynamic 3D building models), Photogrammetric Journal of Finland, vol. 15, nr. 2, pp. 48-61

*Höhle, J., 1997c, Computer Assisted Teaching and Learning in Photogrammetry, ISPRS Journal of Photogrammetry and Remote Sensing, vol. 52, nr. 6, pp. 266-276

*Höhle, J., 1996a, Experiences with the Production of Digital Orthophotos, Photogrammetric Engineering & Remote Sensing, vol. 62, no. 10, pp. 1189-1194

Höhle, J., Jørgensen, M. P., 1996b, Photogrammetry for 3D-Visualisation: Rendition with off-the-shelf Software, GIM International, vol. 10, nr. 3, pp. 52-55

Höhle, J., 1996c, Fotorealistiske 3D-modeller af landskabet og huse (Photo-realistic 3D models of landscape and houses, in: Tidsskrift for Kortlægning og Arealforvaltning. Vol. 38, nr. 3, pp. 150-154

Höhle, J., 1995, Die Ergänzung von Karten mittels Photo-CD Bildern (Supplementing of maps by Photo-CD images, Zeitschrift für Photogrammetrie und Fernerkundung, vol. 63, nr. 2, pp. 69-78

Höhle, J., Damgaard-Iversen, J., 1994. Standarder for billeder og rastergrafik (Standards for images and raster graphics. In: GIS i Danmark (GIS in Denmark), Teknisk Forlag A/S, Copenhagen, ISBN 87-571-1775-6, pp. 193-201

Höhle, J. 1994, Die Vermessung von Flachwassergebieten aus der Luft – Beispiele aus Dänemark (Surveying of shallow water areas from the air – examples from Denmark), Zeitschrift für Vermessungswesen, 119. Jg., nr. 3, pp. 129-144

Höhle, J., 1993a, Den objekt-orienterede højdemodel (The object-oriented height model), Landinspektøren, nr. 2, pp. 394-400

Höhle, J., 1993b, Height models and digital orthophotos in GIS, Geo-Informations Systeme, vol. 6, nr. 4, pp.17-22

Höhle, J., 1992a, Herstellung von Orthophotos mit einer Arbeitsstation des Geo-Informationssystems Intergraph TIGRIS, Zeitschrift für Photogrammetrie und Fernerkundung, vol. 60, nr. 2, pp. 42-48

Höhle, J., 1992b, The Object-Oriented Height Model and its Application, International Archives of Photogrammetry and Remote Sensing, vol. XXIX, Part B4, Commission IV, pp. 868-873

Höhle, J., 1991, Zur Anwendung digitaler Orthophotos in Geographischen Informationssystemen (On the application of digital orthophotos in geographic information systems), Geo-Informations-Systeme, vol. 4, nr. 4, pp.7-13

Höhle, J., 1990a, Om anvendelsen af digitale ortofotos i LIS/GIS (On the application of digital orthophotos in LIS/GIS), Skriftserie Institut for Samfundsudvikling og Planlægning, nr. 60, pp. 11

Höhle, J., 1990b, Versuche zur photogrammetrischen Kartierung von Küsten (Experiments on the photogrammetric mapping of coasts), in: Publication series of the

Institute of Surveying and Photogrammetry, Denmarks Technical University in Lyngby, nr. 13. , pp.6-26

Höhle, J., 1988, Bestimmung von Meerestiefen und ihre praktischen Probleme (Determination of water depth in coastal areas and its practical problems), Bildmessung und Luftbildwesen, Heft 4, pp. 131-137

Höhle, J., 1987, Application of Terrain Modelling in Coastal Areas, Proceedings of the International Colloquium "Progress in Terrain Modelling", Lyngby, pp. 167-177

Höhle, J., 1984, Wild Avioplot RAP: A system for plotting, data acquisition and aerotriangulation, Proceedings of the 50th annual meeting of the American Society of Photogrammetry, pp. 812-817

Höhle, J., Pohjola, P., 1983. Instrumentelle und wirtschaftliche Gesichtspunkte bei Projektkartierungen (Instrument-related and economic considerations in mapping projects), Vermessung, Photogrammetrie, Kulturtechnik, Vol. 81, nr. 4, pp.127-133

*Höhle, J., 1983, Performance Parameters of a Digital Plotting Table for Photogrammetry, Photogrammetric Engineering and Remote Sensing, Vol. 49, No. 1, pp. 111-118

*Höhle, J. and A. Jakob, 1981, New instrumentation of direct photogrammetric mapping, Photogrammetric Engineering and Remote Sensing, Vol. 47, No. 6, pp. 761-767

Höhle, J., 1980, Die graphische Ausgabe am analytischen Auswertegerät Aviolyt AC1 mittels des neuen Digitalzeichentisches TA2 (The graphical output at the analytical Plotter Aviolyt AC1 by means of the new digital plotting table TA2), Bildmessung und Luftbildwesen, Heft 5, pp. 77-87

Höhle, J., 1979a, Der intelligente Digitalzeichentisch – eine Neuerung für die photogrammetrische Kartierung (The intelligent digital plotting table – an innovation for photogrammetric mapping), Vermessung, Photogrammetrie, Kulturtechnik, 2, pp. 25-32

Höhle, J., 1979b, Ein photogrammetrischer Zeichentisch mit Rechnersteuerung (A photogrammetric plotting table with computer control), Bildmessung und Luftbildwesen, Heft 3, pp. 75-80

Höhle, J., Stewardson, P., 1977a, Orthophotogeräte und ihre Wirtschaftlichkeit, (Orthophoto Instruments and their Economics), Bildmessung und Luftbildwesen, vol. 45, no. 1, pp.7-14

*Gut, D. , Höhle, J., 1977b, High-altitude photography – aspects and results, Photogrammetric Engineering and Remote Sensing, 43 (10), pp. 1245-1255

Höhle, J., Schneider, H., 1973a, The Use of the Wild PPO-8 Orthophoto Equipment for the A8 Autograph, Proceedings of the Orthophoto Workshop II, San Jose, California, USA, pp. 76-97.

Höhle, J., 1973b, Production Results with the Wild PPO-8 Orthophoto Equipment, Proceedings of the ASP Fall Convention, Orlando, Florida, U.S.A., pp. 39-56

Okamoto, A., Höhle, J., 1972, Allgemeines analytisches Orientierungsverfahren in der Zwei- und Mehrmedienphotogrammetrie und seine Erprobung (General method for analytical orientation in two- and multi-medium photogrammetry and its testing), Bildmessung und Lufbildwesen, vol. 40, pp. 103-106 & 112-119

Höhle, J., 1972, Methoden und Instrumente der Mehrmedienphotogrammetrie (Methods and instruments of multi-medium photogrammetry), invited paper to the 12th International Congress of Photogrammetry, Commission 2, International Archives of Photogrammetry, pp. 14.

*Höhle, J., 1971, Reconstruction of the underwater object, Photogrammetric Engineering, 37 (9), pp. 948-954

Höhle, J., 1967, Zur Genauigkeit photogrammetrischer Kartierungen bei flachem Gelände (On the accuracy of photogrammetric mapping at flat terrain), Bildmessung und Luftbildwesen, Vol. 35, nr. 3, pp. 105-113

Publications of other authors

Books on the subject

Balstrøm, T., Jacobi, O., Bodum, L., 2006, Bogen om GIS og geodata (Book on GIS and geodata), ISBN 87-991446-0-3, pp. 327

Kraus, K., 1996, Photogrammetrie (Photogrammetry), Vol. 2, Ferd. Dümmlers Verlag, Bonn, ISBN 3-427-78653-6, pp. 488

Li, Z., Zhu, Q. and Gold, C., 2005, Digital Terrain Modeling – Principles and Methodology, CRC Press, ISBN 0-415-32462-9, pp.323

Maune, D.F. (editor), 2007, Digital Elevation Model Technologies and Applications: The DEM User Manual, 2nd Edition, ISBN 1-57083-082-7

Luhmann, T., Robson, S., Kyle, S., Harley, I., 2006, Close Range Photogrammetry, Whittles Publishing, ISBN 1-870325-50-8), pp. 510

Research on the subject

Eeg, J., Peng, L., Frederiksen, P., 1990, Måling af højdedata med korrelator i billeder 1:18000 (Measurement of elevation data by correlator using images 1:18000), in: Publication series of the Institute of Surveying and Photogrammetry, Denmarks Technical University in Lyngby, nr. 13, pp.54-85

El-Hakim, S., 2008, 3D-data modelling and visualization, in: Advances in Photogrammetry, Remote Sensing and Spatial Information Science (2008 ISPRS Congress Book), CRC Press, ISBN 978-0-415-47805-2, London, pp. 311-322

EuroSDR 2007, Proceedings of the International Workshop on Land and Marine Information Integration, Malahide, Dublin, Ireland, Official Publication no. 52, ISBN 9789051795660, CD publication

Guenther, G.C. 2007, Airborne Lidar Bathymetry, in: Maune, D.F. (editor), Digital Elevation Model Technologies and Applications: The DEM User Manual, 2nd Edition, ISBN 1-57083-082-7, pp. 253-320

Haala, N., Wolff, K., 2009, Digitale photogrammetrische Luftbildkamerasysteme – Evaluation der automatischen Generierung von Höhenmodellen (Digital photogrammetric aerial camera systems – evaluation of the automatic generation of elevation models), Proceedings of the annual meeting of the German Society for Photogrammetry, Remote Sensing and Geoinformation in Jena, ISSN 0942-2870, vol. 18, pp. 23-32

Heipke, C., Jacobsen, K., and Wegmann (Eds.), 2002, Official Publication of the European Organization for Experimental Photogramemtric Research (OEEPE), no. 43, ISBN 3-89888-864-9, pp. 297

Jacobi, O., 1994. Digitale højdemodeller (Digital terrain models), in: GIS i Danmark (GIS in Denmark). Teknisk Forlag A/S, Copenhagen, ISBN 87-571-1775-6, pp. 61-71

Jacobi, O., 1977. Om punkttæthed, målenøjagtighed, terræntype og opmålingsøkonomi (On point density, measuring accuracy, terrain type and economy in surveying), in: Publication serie of the Institute of Surveying and Photogrammetry, Denmarks Technical University in Lyngby, nr. 9. , pp. 101-117

Jacobsen, K., Crespi, M., Fratarcangeli, F., Giannone, F., 2008, DEM Generation with CARTOSAT-1 Stereo Imagery, Earsel Joint Workshop Remote Sensing, Bochum, pp.8

Kralova, V., 2008, Application of Digital Photogrammetry, Modern Visualization Methods and GIS Technology for Monument Preservation, PhD thesis at CTU in Prague, pp. 133

Mallet, C., Bretar, F., 2009, Full-waveform topographic lidar: State-of-the-art, ISPRS Journal of Photogrammetry and Remote Sensing 64, pp. 1-16

Mercer, B., Schnick, S.,1999, Comparison of DEMs from STAR-3i Interferometric SAR and Scanning Laser, Proceedings of the ISPRS Commission III workshop in La Jolla, CA, U.S.A., pp. 8

Pedersen, M., B., 1999, OEEPE Test on Automatic Orientation – a Solution from Aalborg, in: OEEPE Official publication nr. 36, pp. 139-144

Potuckova, M., 2006, Image Matching and its Application in Photogrammetry, PhD thesis at CTU in Prague, in: Working papers from the Department of Development and Planning, nr. 314, ISBN 87-91830-00-1, ISSN 1397-3169, pp. 132

Wind, M., 2008, Automatic Generation of Elevation Data over Danish Landscape, PhD thesis at Aalborg University, pp. 125

Abbreviations

AAU	Aalborg University
ALS	Airborne Laser Scanning
CityGML	City Geographic Mark up Language
CCD	Charge Coupled Device
ENC	Electronic Nautical Chart
DEM	Digital Elevation Models
DDO	Denmark's Digital Orthophoto
DTM	Digital Terrain Model
DSM	Digital Surface Model
DMC	Digital Mapping Camera
EuroSDR	European Spatial Data Research
FOV	Field Of View
GIS	Geographic Information System
GPS	Global Positioning System
GSD	Ground Sampling Distance
GB	Giga Byte
IMU	Inertial Measuring Unit
INS	Inertial Navigation System
MHHW	Mean Higher High Water
MLLW	Mean Lower Low Water
NMAD	Normalized Median Absolute Deviation
OEEPE	European Organization for Experimental Photogrammetric Research
RMSE	Root Mean Square Error
RTK	Real Time Kinematic
SAR	Synthetic Aperture Radar
TIN	Triangulated Irregular Network
VRML	Virtual Reality Modelling Language
X3D	Extensible 3D Graphics
3D City Model	Three-Dimensional City Model

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