TECHNISCHE UNIVERSITÄT DRESDEN

Faculty of Environmental Sciences Institute for Cartography

MASTER'S THESIS

HYBRID AUTOSTEREOSCOPIC 3D METHODS FOR DEPICTING HIGH-RELIEF TERRAIN

CASE STUDY: DACHSTEIN, AUSTRIA

JEFF WELTER

Mat-Nr. 38387385

Supervisors: Prof. Dr. Manfred F. Buchroithner, Dipl.-Geogr. Benjamin Schröter

Institute for Cartography, TU Dresden

Dresden, October 14, 2013

TABLE OF CONTENTS

DECLARATION OF ORIGINALITY

I hereby declare that the submitted diploma thesis entitled

Hybrid Autostereoscopic 3D Methods for Depicting High-Relief Terrain – Case Study: Dachstein, Austria

is my own work and that, to the best of my knowledge, it contains no material previously published, or substantially overlapping with material submitted for the award of any other degree at any institution, except where acknowledgement is made in the text.

Dresden, October 14, 2013

Jeff Welter

TECHNISCHE UNIVERSITÄT DRESDEN

Faculty of Environmental Sciences Institute for Cartography

TASK OF MASTER THESIS

Course of Studies: Cartography

Name of Graduand: Welter, Jeffrey Thomas

Topic: Hybrid Autostereoscopic 3D Methods for Depicting High Relief Terrain: Case Study - Dachstein, Austria

Task Description and Goals:

Although True 3D maps are becoming more and more commonplace, there are still many areas in which their utility and accessibility may be improved. Two of these are autostereoscopic and multi-stereoscopic 3D maps– maps that can be viewed in 3D without external aids like glasses and that can be viewed by multiple viewers simultaneously.

The object of this thesis is to demonstrate the advantages and disadvantages of two different hybrid methods for creating multiviewer-capable autostereoscopic 3D maps of high-relief terrain, using as a case study the example of depicting the Dachstein Massif in Austria.

The first method is to combine a 3D digital model created using the multistereoscopic Structure from Motion technology and a lenticular foil display to create a large (approximately 5 m x 2 m) transversal multiviewer autostereoscopic representation of the Dachstein Südwand.

The second method is to generate a 3D physical model using Digital Terrain Model (DTM) data of the Dachstein Massif to control a Computer Numerical Control (CNC) milling machine to create a mold for a solid terrain model which will then be finished by hand using traditional methods. This method changes the interface between “human” and “machine” in the production of solid terrain models.

Since these two hybrid methods have not been attempted before, they both will be global innovations when completed.

The major findings have to be presented in the form of an A0 colour poster and a paper of 5 to 6 pages.

Supervisors:	Prof. Dr. Manfred Buchroithner
	Dipl.-Geogr. Benjamin Schröter
Delivered:	May 13, 2013
Date of submission:	October 14, 2013

Prof. Dr. Manfred Buchroithner Dipl.-Geogr. Benjamin Schröter

LIST OF FIGURES

NOTE: All non-credited photos are by the author

LIST OF ABBREVIATIONS

ALS	Aerial Laser Scanning
CNC	Computer Numerical Control
DEM	Digital Elevation Model
DSM	Digital Surface Model
DTM	Digital Terrain Model
FDM	Fused Deposition Modeling
IfSAR	Interferometric Synthetic Aperture Radar
LFD	Lenticular Foil Display
LiDAR	Light Detection and Ranging
LOM	Laminated Object Manufacturing
MLS	Mobile Laser Scanning
RP	Rapid Prototyping
SfM	Structure from Motion
SL	Stereolithography
SLS	Selective Laser Sintering
SRTM	Shuttle Radar Topography Mission
STM	Solid Terrain Model
TIN	Triangular Irregular Network
TLS	Terrestrial Laser Scanning

ACKNOWLEDGEMENTS

I would like to thank all those without whose help this thesis would not have been completed. First, Prof. Dr. Manfred F. Buchroithner at TU Dresden who supported and encouraged my ideas and was the driving force behind this; also Dr. Bernd Hetze and Prof. Dr. Dirk Stendel for providing technical assistance for the practical portions of the project. At TU München, Stefan Peters for his guidance and for not letting me quit when I struggled under the load. And Dr. Georg Gartner at TU Wien for standing behind the idea that an artist has a place at a technical university.

I would also like to thank the thirteen other students of the 2011 intake of the International Master of Cartography program. Every single one of you has helped me at one time or another over the past two years. You are my friends and I could not have done this without you all.

In addition, Dr. Alan D. Manning whose support has made it possible to "keep body and soul together" during my studies; my parents, Tom and Kathy Welter, who gave me my love for learning; and my sister, Jackie Gratton, for never doubting that I could do this (I am the Bezwinger!).

And finally, my wife Tina, who was willing to give up her home and art studio, leave friends and family, and move halfway around the world to cities where she'd never been and a language that she didn't speak; words are not enough to express my gratitude. This thesis is your accomplishment too.

ABSTRACT

The advances in 3D technology in the field of Cartography necessitate a reevaluation of how high relief topography has been and should be depicted. Autostereoscopic 3D, which does not require the use of external viewing aids in order for the subject to be perceived with a spatial impression, and which has multiviewer capability is proposed as a desirable method. Autostereo-scopic 3D displays have the potential for improving not only the quality of the depictions, and increasing their availability for use by scientists or the general public.

In the theoretical portion of this study, autostereoscopy is defined and explained. Historical methods of autostereoscopic 3D presentation of high relief terrain, in the form of landscape relief models also known as solid terrain models (STM), are reviewed. An STM is created with these methods in order to understand the process and how it could be adapted to use modern technologies. Digital 3D models and the methods of generating them are discussed, in particular laserscanning and Structure from Motion (SfM). Lenticular foil displays (LFD) are presented as an alternative method for multiviewer autostereoscopic 3D presentations.

In the practical portion of this study, two hybrid methods for creating autostereoscopic 3D depictions of high relief terrain, each having a digital and a physical component, are suggested for experimentation. A project is carried out utilizing each method and the results are evaluated. The importance of further research into these hybrid methodologies is discussed.

Keywords: autostereoscopy, true-3D, landscape relief model, solid terrain model, lenticular foil, laserscanning, Structure from Motion, 3D printing, stereolithography, CNC milling, fused deposition modeling

KURZFASSUNG

Die Fortschritte in der 3D-Technologie im Bereich der Kartographie machen eine Neubewertung von Hochrelieftopographie notwendig und sollten verdeutlicht werden. 3D-Autostereoskopie, die keine Verwendung von externen Sehhilfen erfordert, um das Objekt in einem räumlichen Eindruck wahrzunehmen und welche eine Multiviewer-Fähigkeit besitzt, wird als angestrebtes Verfahren vorgeschlagen. Autostereoskopischen 3D-Displays haben nicht nur die Verbesserung der Qualität der Darstellungen als Potenzial, sondern auch ihre erhöhte Verfügbarkeit für die Nutzung durch Wissenschaftler oder der allgemeinen Bevölkerung.

Im theoretischen Teil dieser Studie wird Autostereoskopie definiert und erklärt. Historische Methoden der autostereoskopischen 3D-Darstellung der Hochreliefgelände, in Form von Landschaftsreliefmodelle, auch als feste Geländemodelle (STM) bekannt, werden vorgestellt. Ein STM wird mit diesen Methoden erstellt, um den Prozess zu verstehen und wie er an das moderne Verfahren angewendet werden könnte. Digitale 3D-Modelle und die Methoden zu ihrer Erzeugung werden erörtert, insbesondere Laserscanning und Struktur von Motion (SFM). Lenticular-Folien-Displays (LFD) werden als eine alternative Methode für die Präsentation der 3D-Autostereoskopie für Multiviewer vorgestellt.

Im praktischen Teil dieser Studie werden zwei Hybrid-Verfahren zum Erzeugen von autostereoskopische 3D-Darstellungen von Hochreliefgelände, die jeweils eine digitale und eine physische Komponente besitzen, für Experimente vorgeschlagen. Ein Projekt wird unter Verwendung jeder Methode durchgeführt und die Ergebnisse ausgewertet. Anschließend erfolgt eine Diskussion über die Bedeutung der weiteren Erforschung dieser Hybridmethoden.

Keywords: Autostereoskopie, True-3D, Landschaft Relief, solide Gelände-modell, Lentikularfolie, Laserscanning, Struktur aus Bewegung, 3D-Druck, Stereolithographie, CNC-Fräsen, Fused Deposition Modeling

HYBRID AUTOSTEREOSCOPIC 3D METHODS FOR DEPICTING HIGH-RELIEF TERRAIN

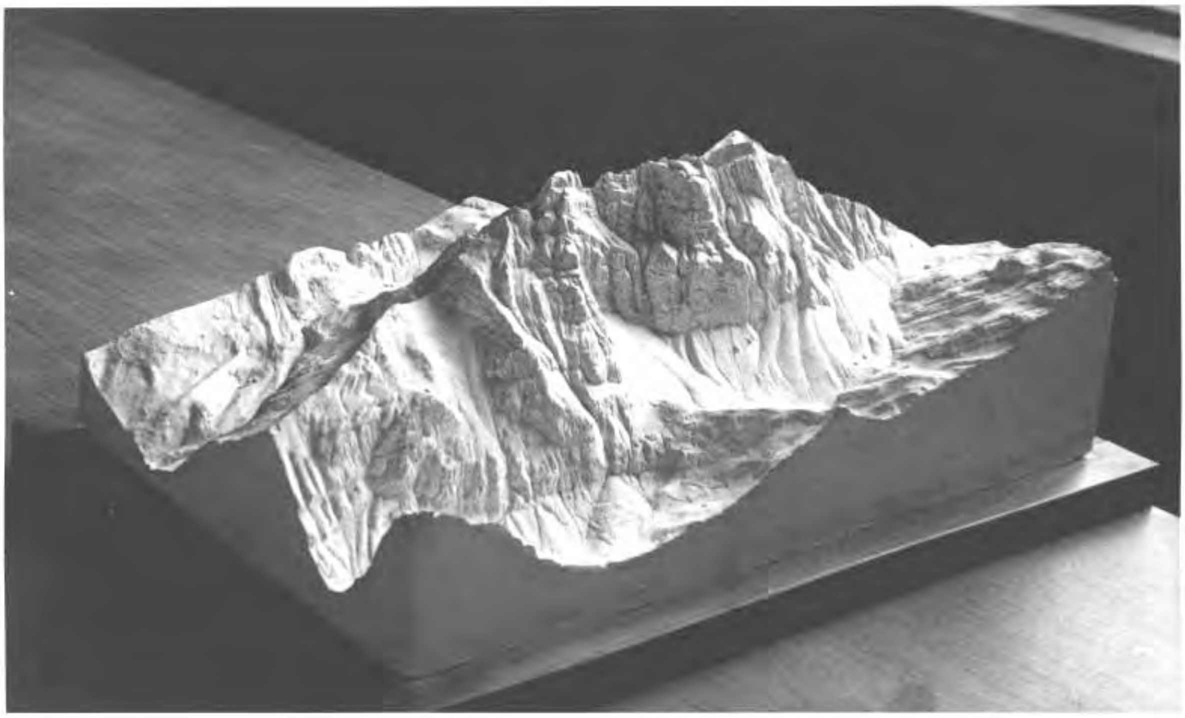
CASE STUDY: DACHSTEIN, AUSTRIA

INTRODUCTION

Advances in digital technology have created new methods for the depiction of cartographic information, especially in the realm of 3D. Traditional methods of depicting topography in high-relief terrain do not take advantage of these advances and therefore are becoming often thought of as old-fashioned or irrelevant. If the goal of cartography is to convey spatial information, these traditional methods need to be reevaluated in light of the new technologies and be either abandoned, updated, or combined with them into what could be termed “hybrid” methodologies.

Solid terrain models are the traditional form of autostereoscopic 3D (viewable without additional viewing aids) depictions of topography. Digital 3D models increase accuracy and save labor, but are not autostereoscopic. Combining the latest 3D technologies with traditional cartographic methods can give improved terrain models at a lower cost, especially for models depicting areas of high topographic relief.

For a test of this, the Dachstein Massif in Austria was chosen as the subject for two projects combining traditional methods and materials with modern digital technologies to create multiviewer autostereoscopic 3D displays.



Source: www.library.ethz.ch

1 AUTOSTEREOSCOPIC 3D

1.1 DEFINITIONS

In order to discuss hybrid autostereoscopic 3D methods used in cartography, the principles upon which they are based must be established through the definition of the terms involved.

- **Stereoscopic vision**, the ability to perceive spatial depth, is the way in which most humans perceive the world and their surroundings.

Stereoscopic vision can be divided into two categories:

- **Monocular stereoscopic vision** uses cues in our environment (occlusion, shadows, proportions, movement, etc.) to allow perception of space.

- **Binocular stereoscopic vision** combines **convergence**, the intersection of the eye axes, and **accommodation**, the automatic focusing of the eyes on a point, to allow an unambiguous perception of space (Stilla 2011).

Binocular stereoscopic vision can be further broken down into two categories:

- **Natural stereoscopic vision** in which two simultaneous views of an object are ‘fused’ into a single view in the brain (Figure 1.1).

- **Artificial stereoscopic vision** in which the object can be replaced by two images of that object, taken from different points of view (Figure 1.2).

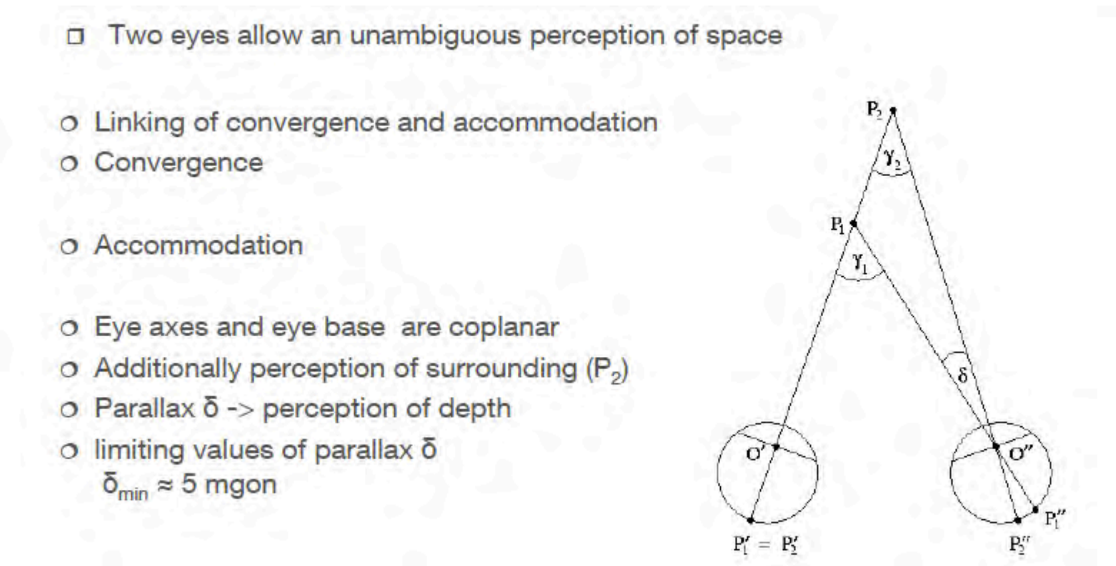


Figure 1.1 Natural stereoscopic vision

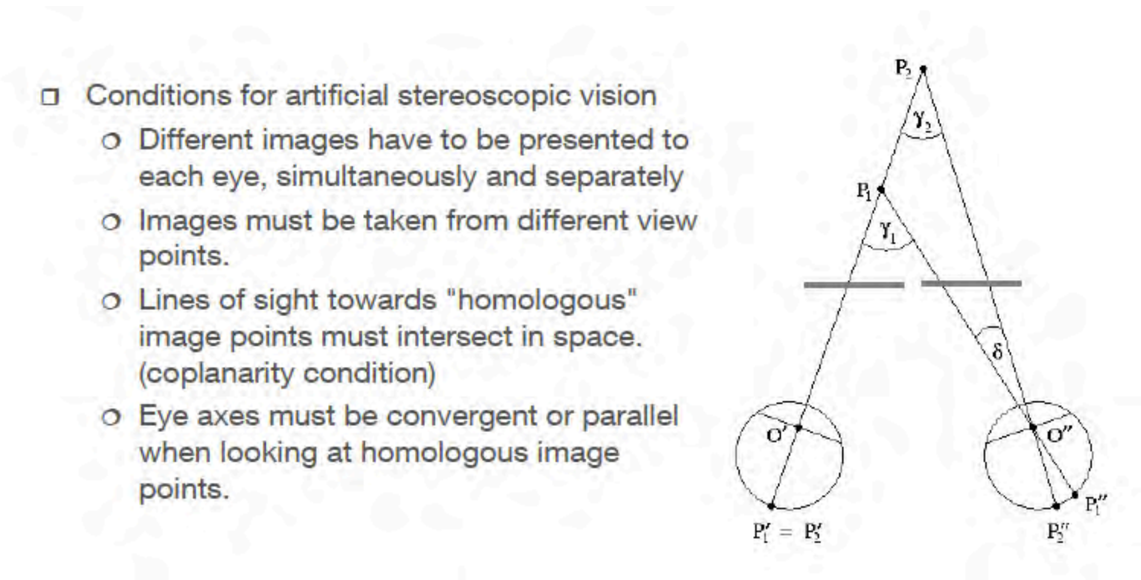


Figure 1.2 Artificial stereoscopic vision

Source (both figures): Stilla 2011

- **Stereoscopic displays**, presentations of images that can be viewed in 3D, the term “3D” being a ‘shorthand’ designation for spatial perception in three dimensions, can be **analog** or **digital**, these being commonly referred to as ‘hardcopy’ and ‘softcopy’ respectively (Buchroithner and Knust 2013a). They can also be further divided into two types:

- **Nonautostereoscopic 3D** is artificial binocular stereoscopy requiring the use of glasses or other similar viewing aids to achieve spatial impression.

- **Autostereoscopic 3D** is binocular stereoscopy without the use of an external viewing apparatus. Autostereoscopic 3D can be attained through either natural binocular stereoscopy or artificial binocular stereoscopy. This can also be referred to as **True 3D**.

Dodgson (2005) states “Most of the perceptual cues that humans use to visualize the world’s 3D structures are available in 2D projections.” This is the essence of cartography; depicting the three dimensional (3D) world with two dimensional (2D) representations. However, many inexperienced map users have difficulty interpreting topographic features on conventional 2D maps (Popelka and Brychtova 2013). Stereoscopic displays can help to overcome this difficulty by requiring less prior knowledge or interpretation on the part of the viewer.

Another factor that must be considered is:

- **Multiviewer capability**, the ability for a stereoscopic display to be viewed simultaneously by more than one observer.

Autostereoscopic 3D displays have an advantage in this instance due to not requiring multiple sets of viewing aids to be available to observers, thus reducing costs and increasing convenience for the viewers. Simultaneous observation also allows for easier interaction and discussion among the viewers.

Two groups of methods can be used to create multiviewer autostereoscopic 3D: **physical** and **digital**.

1.2 PHYSICAL METHODS

One method for a multiviewer autostereoscopic display is to create a physical embodiment of the spatial data. This embodiment can be perceived optically or haptically (via the sense of touch). Geospatial data presented in this manner often takes the form of a **solid terrain model** (STM).

Solid terrain models, also known as **landscape models** or **topographic reliefs**, have a long history and a special place in Cartography as being the original autostereoscopic displays. But because of this long history and in relation to modern technology, they are sometimes considered to be ‘old fashioned’, obsolete, or even irrelevant.

For viewing in true 3D, solid terrain models still have some advantages over newer technologies. Landscape models require no special viewing apparatus such as polarized glasses or 'shutter' glasses. They are instantly understandable to an untrained viewer; no interpretation of contours or shading is required (Buchroithner and Knust 2013).

And they are attractive to viewers. A study conducted between 1992 and 1997 demonstrated that in a setting where both 2D displays and a landscape model are present, approximately 73% of people will spontaneously go to the model within 30 minutes of becoming aware of it (Buchroithner 2007). According to Rase (2012), when shown a solid terrain model “nearly everyone spontaneously tried to touch the surface of the model.” This attractiveness is an important factor for conveying information in this digital age with so many presentation options competing for attention.

The principle of solid terrain modeling is to create a scale representation of a portion of the earth’s surface (Figure 1.3). Conventional maps depict the horizontal dimensions of an area to scale and use a variety of cartographic techniques to represent or symbolize the vertical dimension. The techniques include contour lines, hypsometry, topographic shading and rock depiction.

In contrast to this, a solid terrain model accurately portrays the surface in all three dimensional axes. A physical model has an advantage over a 2D map in that the view can compare heights, understand ambiguities in the landscape, or reveal areas that might be obscured in a

Figure 1.3 Principle of solid terrain modeling

Source: www.library.ethz.ch

conventional depiction by simple head or body movements (Rase 2012). Not only are specialized viewing tools not required, but neither is a legend or explanation of the symbology used in the depiction.

1.2.1 Traditional Construction Methods

From the first landscape models in the 18th century until the introduction of digital 3D printing technology at the end of the 20th century, the methods for constructing a topographic relief have remained relatively unchanged. Techniques pioneered by notable cartographers and relief builders of the past such as Xavier Imfeld, Simon Simon, Carl Meili, Fridolin Becker, Eduard Imhof (Figure 1.4), and Alessio Nebbia are still used today by contemporary relief builders such as Toni Mair (Mair and Grieder 2006).

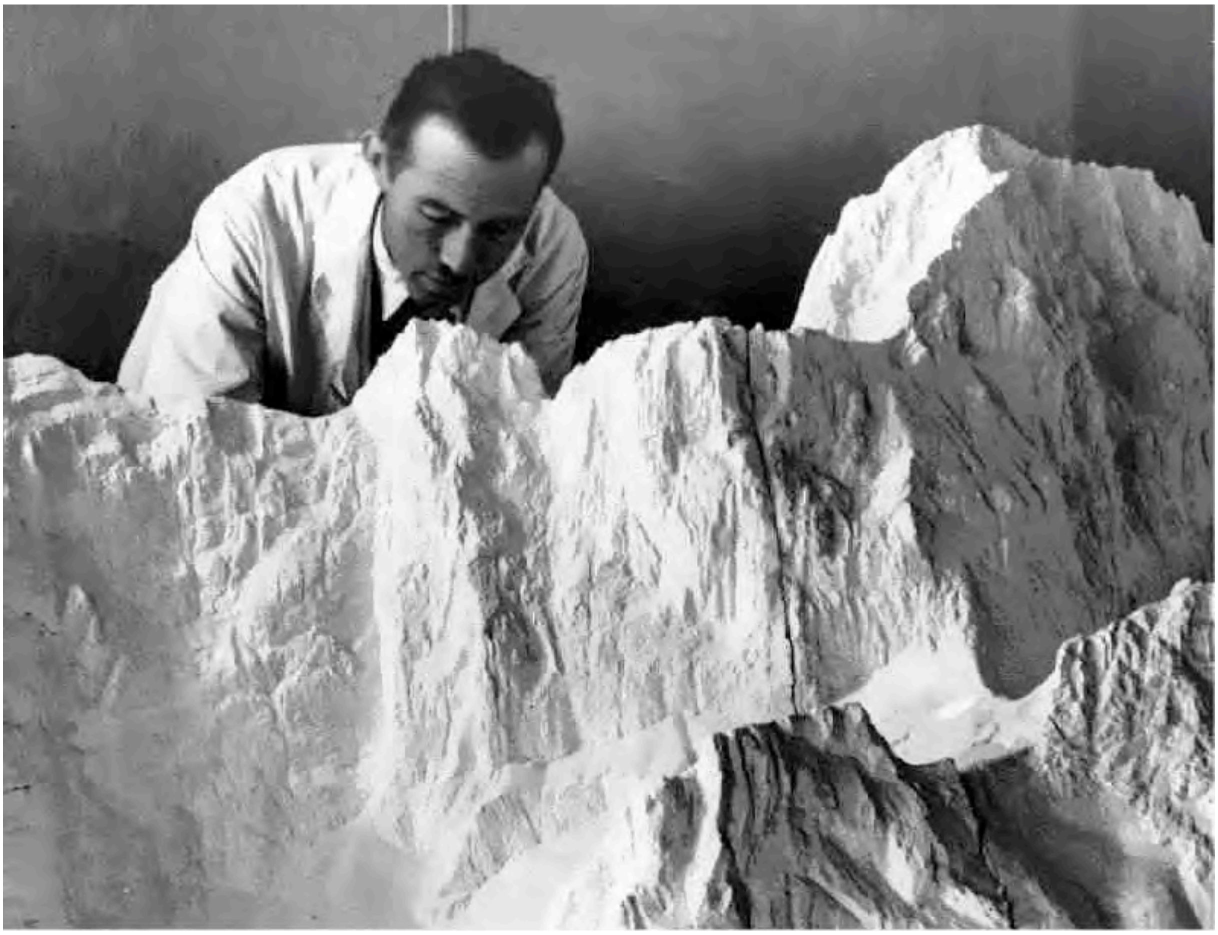


Figure 1.4 Eduard Imhof working on the Windgällen relief, 1938.

Source:www.library.ethz.ch

But traditional handmade landscape models have one major drawback– the amount of labor involved to create one. There have been various methods used over the years to create landscape models, but almost all have one element in common: the **step model** (Figure 1.5).

A step model can be considered the **core** of a topographic relief model; it defines the spatial dimensions of the final product. To create one, the approximate shape of the landscape is built by stacking layers or 'steps' of material which has been cut following the contour line of a specified elevation. The thickness of the material must correspond to the scale contour interval. Once the step model is completed, a surface layer of a carvable material, usually gypsum plaster, is applied by hand. It is into this layer that the fine details of the landscape are carved by the cartographer.

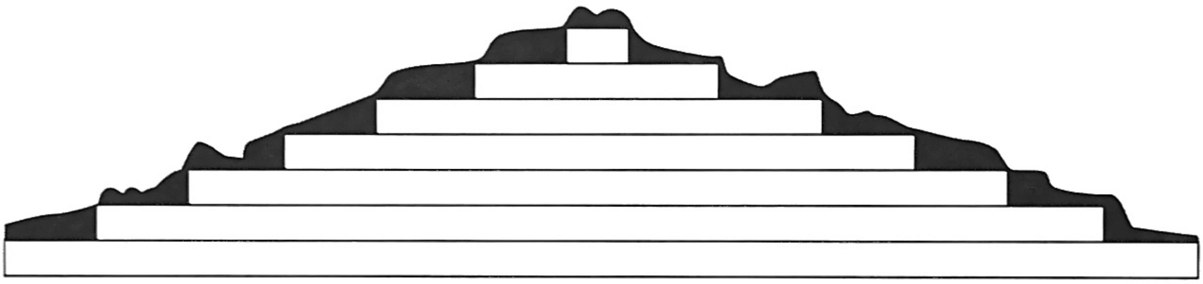


Figure 1.5 Principle of a step model (adapted from Räber 2006)

To illustrate the process of creating a solid terrain model using traditional methods, an example depicting the Grossglockner peak in Austria is shown in the next section. Although some of the materials used are modern, the process itself is consistent with that of the past.

1.2.2 Creating a topographic relief model

The first step in any project of this type is to gather the requisite source materials. In this case, these included various maps, aerial photos, and images and information posted on the internet. The main source map, the Alpenvereinskarte of the Glocknergruppe, was enlarged to the selected scale of 1:5000 (Figure 1.6).

Next, materials were obtained. The core of the relief was built from 5mm thick foamcore board (Figure 1.7). A 40x40cm wooden base was also acquired. The horizontal dimensions of the model were determined based on which features of the mountain would be included at the selected scale.

At a scale of 1:5000, the 5mm thickness of the board sis equivalent to 25m. However, the contours on the base map were drawn at 20m intervals, so new 25m interval contours were interpolated onto the map (Figure 1.10, p.12). The model has no vertical exaggeration.

Figure 1.6 Grossglockner STM – References for relief building


Figure 1.7 Grossglockner STM – Materials for a step model

Figure 1.8 Grossglockner STM – Completed step model

Figure 1.9 Grossglockner STM – Initial carving phase

Figure 1.10 Grossglockner STM – Topographic map showing interpolated contours

Each contour was transferred to board and the shape cut out. This was a very time consuming process. The layers were then stacked and glued together to create the core, using special care to maintain correct alignment (Figure 1.8).

After the completed core was attached to the wooden base, an initial layer of plaster was applied, just covering the contours (Figure 1.9). Boards following the profile of each side's cross section were cut from thin plywood and attached to the core. Additional plaster was applied, and surface details were carved using chisels and knives. Information was interpreted from stereo pairs of aerial photos using a stereoscope.

An iterative process of refining the details - carving away material in some areas and adding more plaster in others - was repeated until a satisfactory shape was obtained. Since drying time was required for each addition, this process required many days' effort. A stain of the basic rock color was mixed from water-based paints and applied to the raw plaster. Other stains were made for shadows, highlights, wet areas and also shadows in glacial crevasses. Snowfields were colored with an opaque mix. All coloring detail was derived by comparing numerous photographs.

The final result is effective in portraying the peak and its environs (Figure 1.11). However, it required over 120 hours of labor to create it. This labor-intensive process and the resulting high production costs are the major factors in the relative rarity of solid terrain models as cartographic products (Imhof 2007).

Figure 1.11 Grossglockner STM - Completed landscape model

1.3 DIGITAL METHODS

Digital technologies have completely transformed cartography in the past 30 years. Processes that were once time-consuming and required great skill on the part of the cartographer are now mostly or completely automated, which often results in higher degrees of accuracy and cost effectiveness. But just as importantly, these technologies have also resulted in new ways of presenting spatial information. The creation of autostereoscopic 3D displays can benefit greatly with the incorporation of these methods.

- **Rapid Prototyping** (RP) is the automatic creation of solid objects in a short period of time. It can be used to fabricate solid embodiments of spatial data.

- **Lenticular Foil Display** (LFD) is a hardcopy autostereoscopic method with multiviewer capability of presenting a 3D image or scene.

Rapid Prototyping methods can be subdivided into **additive** processes and **subtractive** processes. Both require the prior creation of a 3D digital model of the object to be fabricated.

1.3.1 Additive Processes

Also known as **3D printing**, additive processes create objects from a 3D digital model by building up small amounts of material, usually layer upon layer (Taktikz 2013). These processes are divided into four groups:

- **Stereolithography** (SL)

- **Fused Deposition Modeling** (FDM)

- **Selective Laser Sintering** (SLS)

- **Laminated Object Manufacturing** (LOM)

For the purpose of this study, only stereolithography and fused deposition modeling will be described.

1.3.1.1 Stereolithography

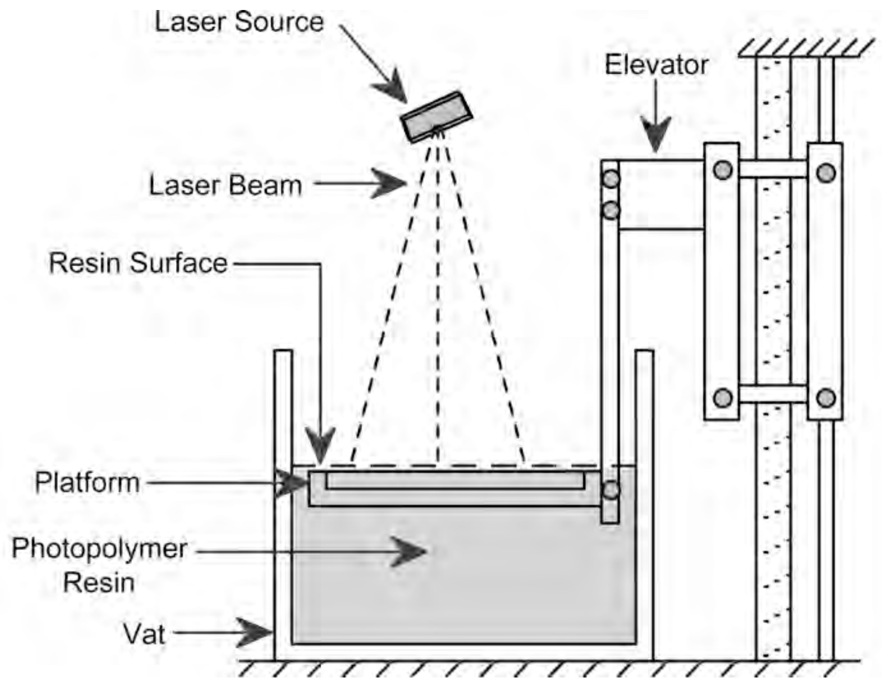


Figure 1.12. Stereolithography (adapted from Zhang 2000)

Stereolithography (Figure 1.12) was the first technique developed for rapid prototyping. Rase (2009) gives the following description:

> A computer-controlled laser beam induces a phase change in a thin layer of photosensitive liquid. The liquid changes phase – becomes solid by polymerization – where the laser beam hits the surface. A new layer is the built on top of the solidified layer, and the procedure is repeated until the object is finished.

Stereolithography using **digital elevation model** (DEM) data enables the rapid production of topographic relief models. Good results are obtained in low relief landscapes, but in high mountain topography the results are less than satisfactory due to the lack of information on vertical or nearly vertical faces. This is because the elevation data has normally been captured from a nadir position and consists only of spot heights, not surface texture.

This situation can best be illustrated with an example: two models of the Eiger in Switzerland are shown below. The model in Figure 1.13 was created from digital elevation data using stereolithography. The model in Figure 1.14 is handmade model by Toni Mair using traditional methods.

Figure 1.13 Eiger North Face model produced by stereolithography

Figure 1.14 Eiger North Face model produced by traditional methods

Source (both figures): Mair 2012

Note the differences within the circled area. The model created with stereolithography is technically accurate; the elevations of the individual points are precise, but there is no information on the vertical surfaces. No information is conveyed beyond the geometric shape. This is a disadvantage of this method for the creation of STMs.

The handmade landscape model overcomes these problems. The viewer can see the structure of the rocks and the effects of the erosive processes. While it may be less precise in an absolute quantificational sense, it does a much better job of communicating spatial information.

1.3.1.2 Fused Deposition Modeling (FDM)

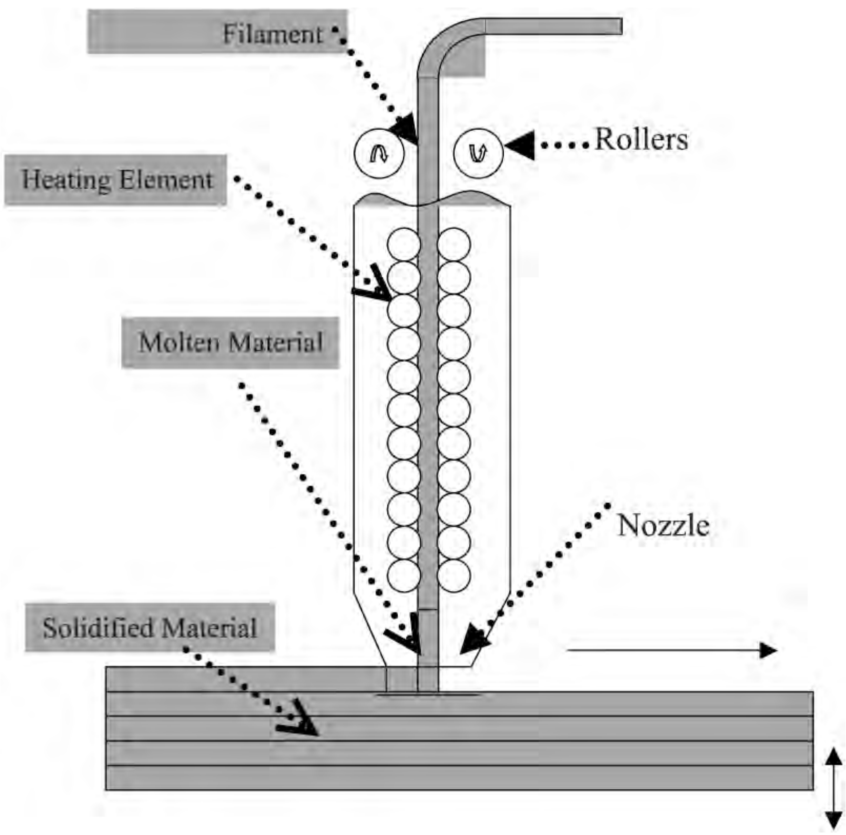


Figure 1.15 3D Printing (FDM) (adapted from Zhang 2000)

In the **fused deposition modeling** (FDM) process (Figure 1.15), thermoplastic material is fed to the print head in a liquid state and built up in layers (Rase 2009). For creating an STM, a digital model generated from DEM data can used as a starting point, but because the model is only a surface, it has no thickness; it must be extruded into a 3D solid using Computer Aided

Design (CAD) software. This solid form must have the property of being ‘watertight’, i.e. having no holes in the triangular mesh. This model is then converted into a stack of 2D slices, i.e. layers for printing.

FDM can build complex shapes quickly and efficiently. Vertical surfaces and even overhangs are within the capabilities. However, if DEM is used as the digital model, the results will be the same as for stereolithography. It is planned to do more research and experimentation with this method in the future.

1.3.2 Subtractive Processes

Subtractive processes rely on the removal of material, usually by the methods of milling, turning/lathing or drilling. Subtractive prototyping is limited to relatively simple shapes - complex geometries are not possible. The material must be readily available in the size and shape needed. And subtractive RP usually takes longer (ProtoCAM 2008).

1.3.3 Computer Numerical Control Milling

Computer Numerical Control (CNC) machines are of two basic types, **CNC routers** and **CNC milling machines**. Both operate on the same basic principle; a computer guides the cutting tool to follow the contour of a 3D digital model.

CNC routers (Figure 1.16) have a greater range of travel in the X and Y (horizontal) axes, but less in the Z (vertical) axis (Weston 2007). In regard to making STMs, CNC routing is more suitable for low-relief landscapes.

CNC milling machines (Figure 1.17) have a greater range of travel in the Z axis and less in the X and Y axes, and are therefore more suitable for high-relief topography.

The recent development of **multi-axis** CNC milling machines, in which it is possible to also rotate the milling head in two or three axes, shows potential for creating detail on vertical surfaces as good or better than FDM (eFunda 2013).

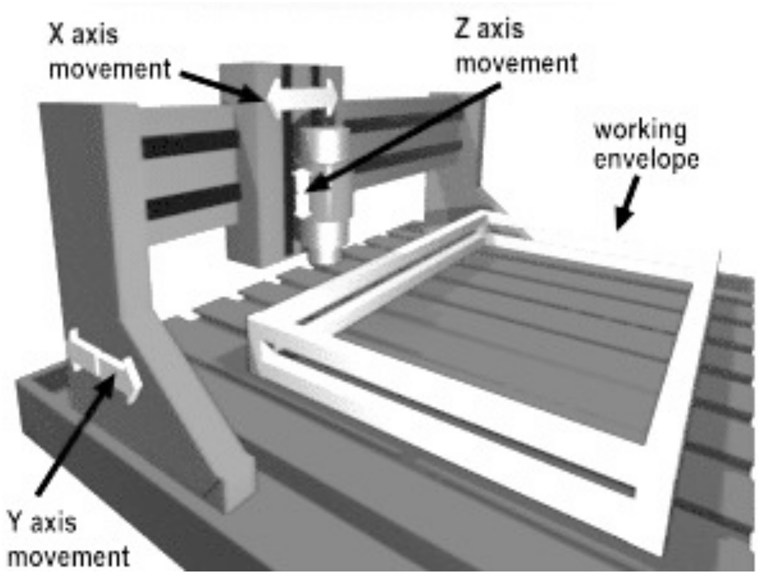


Figure 1.16 CNC router showing working envelope

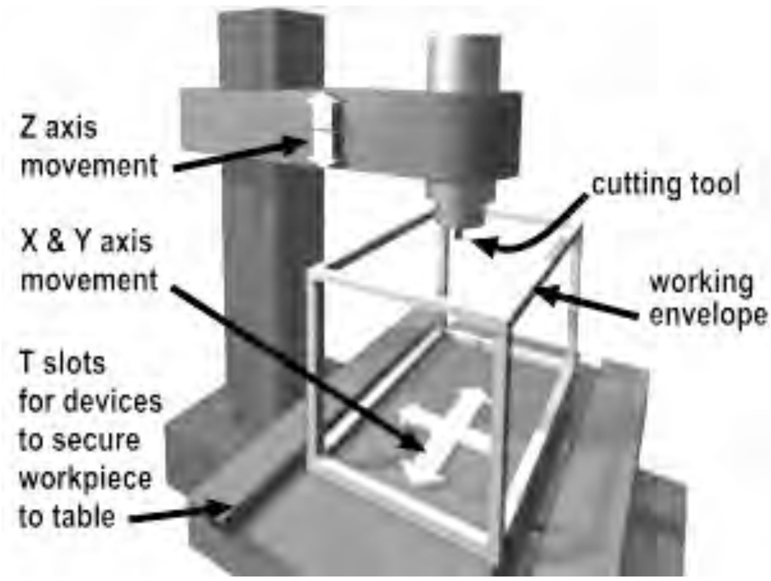


Figure 1.17 CNC milling machine

Source (both figures): www.data-wales.co.uk/cnc_mactype.htm

1.4 LENTICULAR FOIL

All the methods described thus far involve the creation of solid terrain models which rely on natural stereoscopic vision as an autostereoscopic display. Lenticular foil displays differ in that the underlying principle for achieving spatial perception is artificial stereovision.

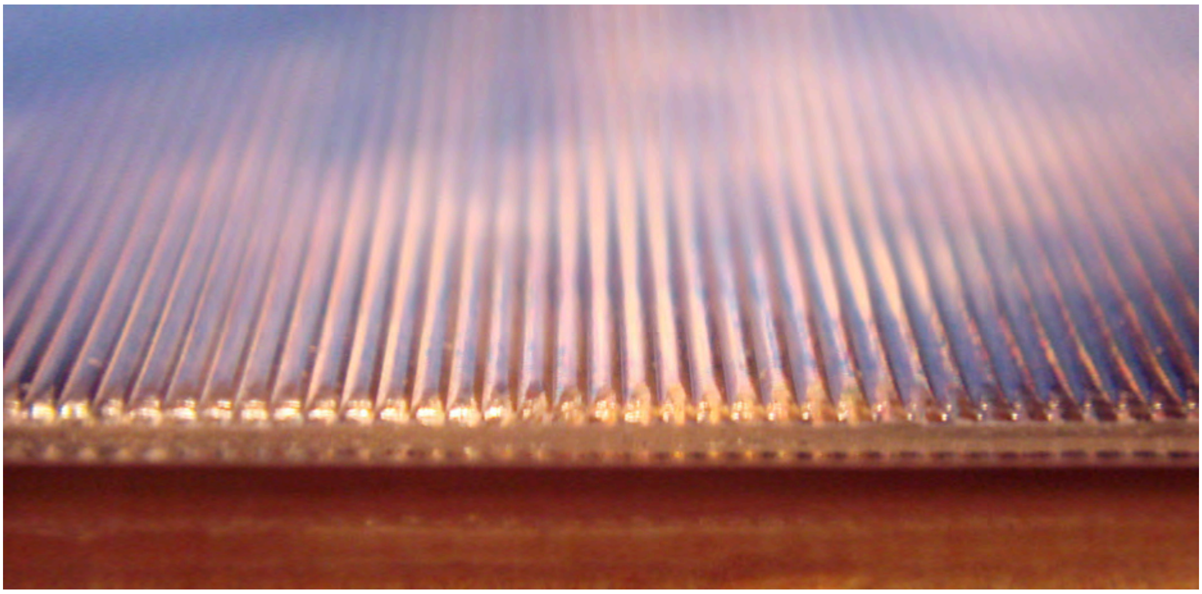


Figure 1.18 Lenticular Foil showing cross-section of linear lenses

Source: Wikimedia Commons

Lenticular foil consists of multiple linear lenses which direct different parts of the image to each eye (Figure 1.18). By interlacing thin strips of each image and accurately locating them behind the lenses, stereovision and perceived depth are achieved for the viewer (Figure1.19). Further details of the optical principles involved are in Habermann 2004, Buchroithner 2005, Knust et. al. 2011, and Stendel 2013.

Lenticular foil can also be used in conjunction with computer monitors to create ‘softcopy’ autostereoscopic displays. For the purpose of this study, only conventional ‘hardcopy’ displays will be considered.

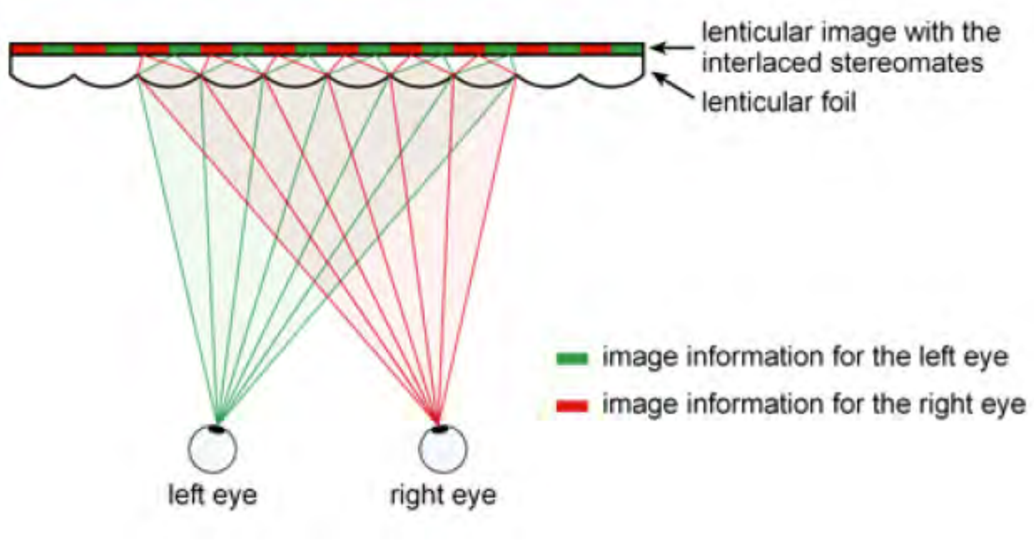
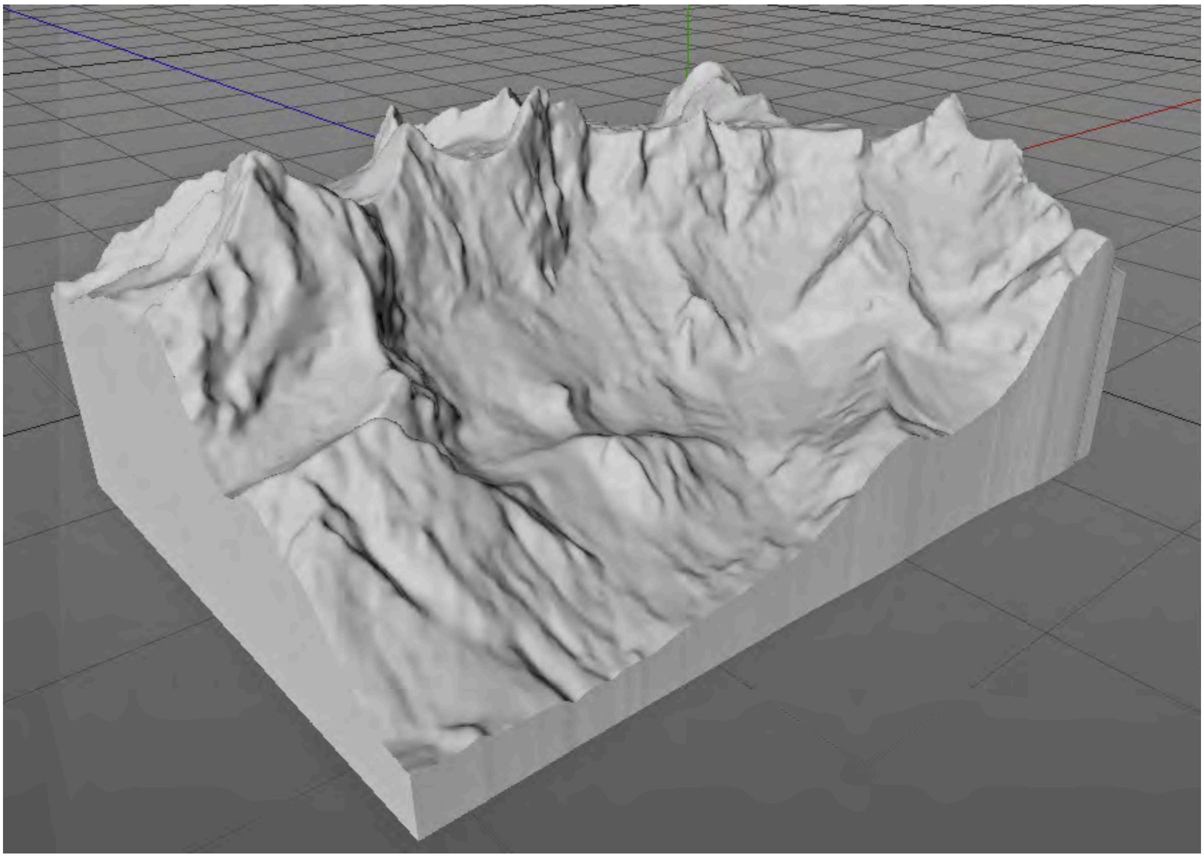


Figure 1.19 Principle of stereovision with lenticular foil (Knust et. al 2011)

The advantage of an LFD is that, while relying on the principle of artificial binocular stereoscopy, no additional viewing aids are required, making it simultaneously autostereoscopic and multiviewer. Also, since the physical form of the display itself is 'flat', it can be exhibited vertically thereby requiring less space than an STM of the same scene.

The processes and methods used in the creation of an LFD differ dramatically from those required to create an STM with automated technologies. Yet the starting point of all of these is the creation of a digital 3D model of the terrain to be represented. The results derived from any of these methods depend on the quality of the digital model. As has already been shown in the example of stereolithography, limitations that result from the use of DEM as the data source for the digital model adversely affect the final product. While this is not a problem in an LFD if the view in the display is a nadir view (corresponding to the aspect from which the data was acquired), if the display is to be an oblique view, the result will be unsatisfactory.



Source: author

2 DIGITAL 3D MODELS

2.1 DEFINITIONS

Before proceeding, definitions should be established to clarify differences in the various types of 3D digital models as used in cartography:

- **Digital Elevation Model** (DEM): a data set consisting of elevations; can be raster- or vector-based. DEM data can be acquired via various means such as laser scanning (ALS, TLS), photogrammetry, radar (SRTM, IfSAR), or land surveying.

- **Digital Surface Model** (DSM): a DEM that includes all objects on the earth's surface: buildings, vegetation, vehicles, etc.

- **Digital Terrain Model** (DTM): a DEM of the bare surface of the earth in which all artificial objects and vegetation have been removed.

- **Triangular Irregular Network** (TIN): a vector-based DEM; commonly called a **mesh** in digital 3D modeling.

With the advent of Google Earth and other similar services, 3D digital landscape models have become almost ubiquitous. Viewers have become accustomed to, and even expect, 3D depictions of the earth's surface. However, these are **pseudo-3D** depictions; they are viewed using monocular stereoscopic vision.

While usually easier to interpret than traditional 2D maps, pseudo-3D depictions have some disadvantages. Softcopy presentations, such as when displayed on a computer monitor, require navigation on the part of the view to maneuver the viewpoint to the desired position. Often this navigation is not simple, quick, or intuitive. Hardcopy presentations, such as printed panoramic views or orthographic projections, are restricted to one viewpoint – the one chosen by the cartographer.

An example of a pseudo-3D softcopy display generated from a digital 3D model (TIN) is shown in Figure 2.1. The 3D digital model shown in this screenshot from Google Earth consists of two parts: a TIN and a **texture** derived from photographs which has been 'mapped' onto the surface. The appearance is good in a distant view, but in a close view (inset; Figure 2.2), the simplified geometry of the TIN is readily apparent.

A higher density TIN, one with more vertices and faces per unit area (Figure 2.3), allows greater detail and results in a better appearance. This is achieved at the expense of higher computational effort.

NOTE: Since raster DEMs consisting of data acquired from a nadir position produce less than satisfactory results in high-relief terrain, as discussed in Sections 1.3.1.1 and 1.3.1.2, only the creation of vector-based TINs will be considered from this point in the study.

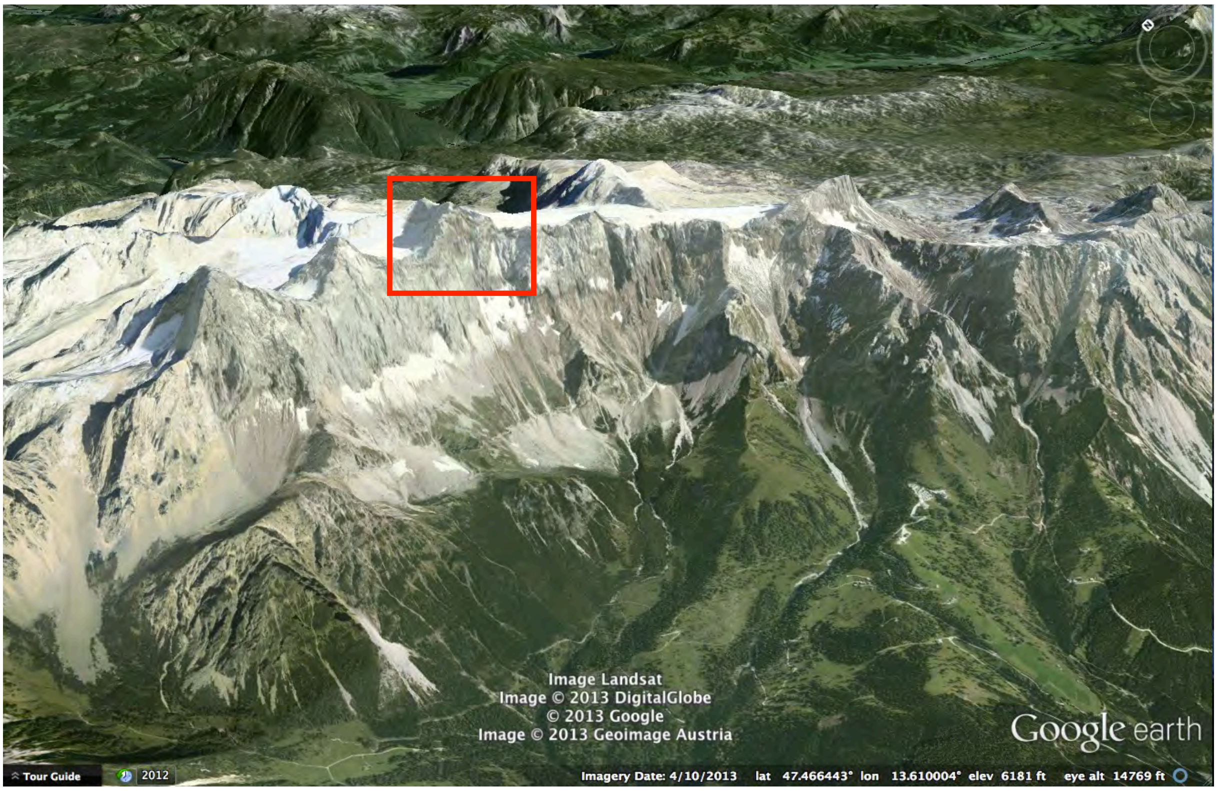


Figure 2.1 Low density TIN – 3D model of the Dachstein Massif. Inset: Hoher Dachstein

Figure 2.2 Low density TIN – Inset view of Hoher Dachstein showing distortion of texture

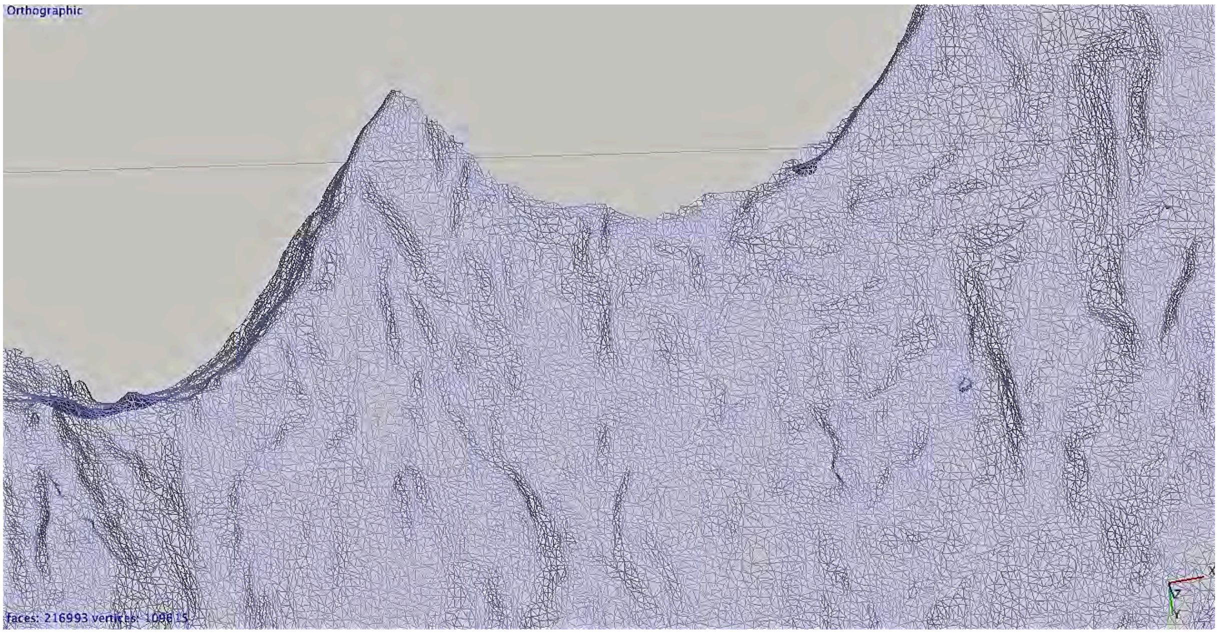


Figure 2.3 High density TIN – Improved relief on vertical portions of Dachstein Südwand

2.2 LASERSCANNING

The principles of laserscanning are well established. Distance measurements are taken via a laser rangefinder at millions of points across a surface or an object. The resultant set of points is called the **point cloud**. The point cloud can be used to reconstruct the shape of the surface or object scanned. The point cloud can also be used to generate geospatial products such as DEMs, building models, or topographic contours (NOAA 2013). Laserscanning, when used for mapping purposes, is usually referred to as LiDAR (**Li**ght **D**etection **a**nd **R**anging).

Laser scans can be acquired in three modes:

- **Terrestrial Laser Scanning** (TLS): a static or stationary mode with the scanner positioned on the earth’s surface

- **Mobile Laser Scanning** (MLS): a kinematic mode with the scanner moving across the earth’s surface during the scan

- **Airborne Laser Scanning** (ALS): a kinematic mode with the scanner moving above the earth’s surface in an aircraft (Figure 2.4)

The mode which should used is determined by the area or object to be scanned. ALS and MLS are usually better suited for large area mapping (Studnicka et. al. 2013).

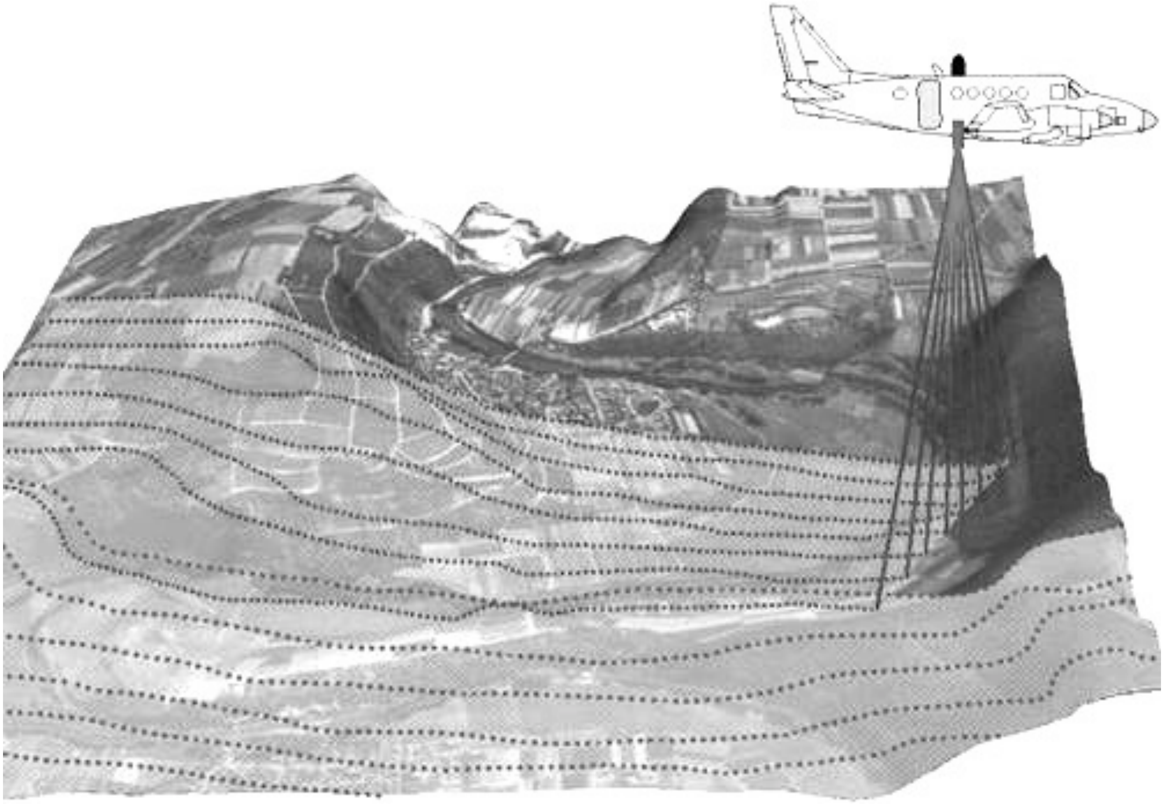


Figure 2.4 Principle of Airborne Laser Scanning (ALS)

Source: www.ikg.uni-hannover.de

2.3 STRUCTURE FROM MOTION (SFM)

The mathematical science of reconstructing 3D from 2D images by matching points and tri-angulation is called **Structure from Motion** (SfM) (Szeliski 2010) (Figure 2.5).

Originating in photogrammetry and computer vision research, SfM enables the creation of 3D digital models without laserscanning. Digital models made with SfM from oblique photos contain more data about the shape of the landscape than just elevation spot heights, resulting in more accurate representation of the landform.

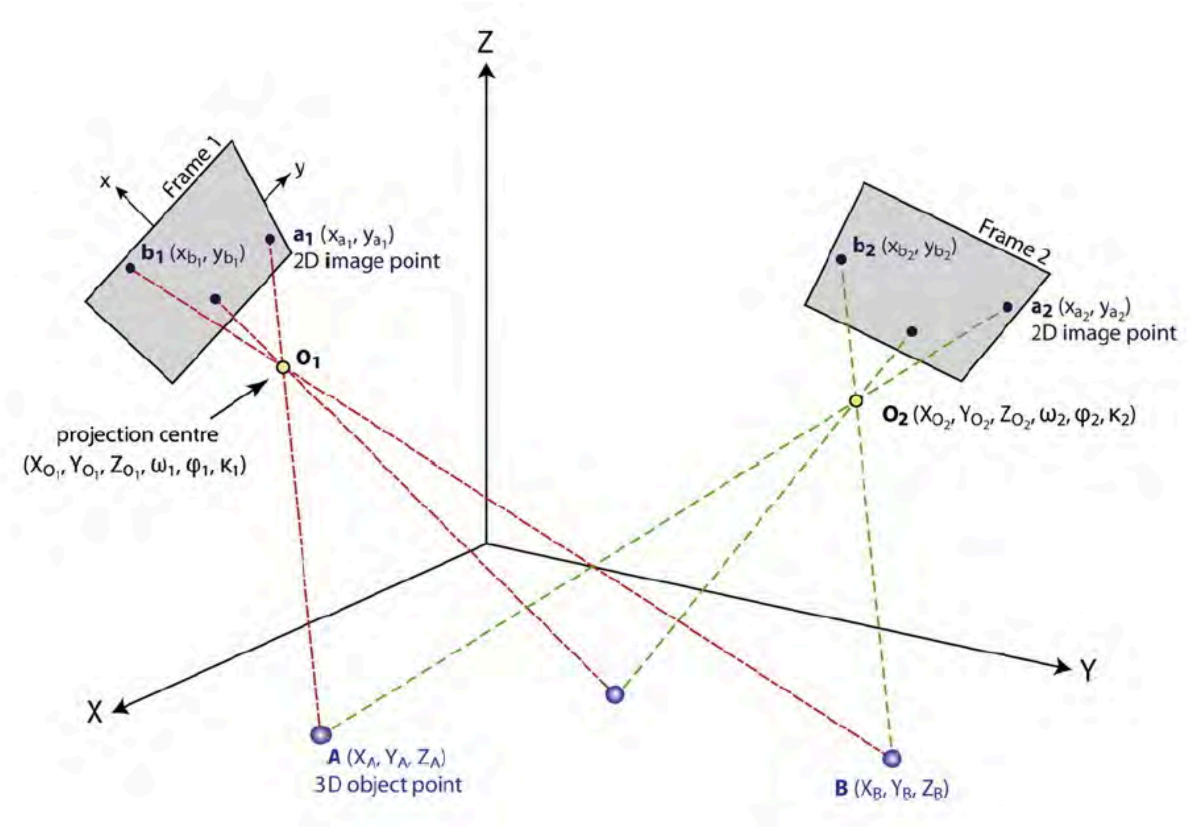


Figure 2.5 Principle of Structure from Motion (SfM) (from Verhoeven et. al. 2012)

The imagery used for SfM reconstruction can be conventional overlapping nadir aerial photos (see Section 4.1.1), but can also be obliquely-acquired photos taken with handheld cameras. Also, prerequisite information is not required for the generation of the model; none of the internal or external parameters of the camera are needed, neither is any information of the time and place of image acquisition (Verhoeven 2011).

In the example in Figure 2.6, twenty-nine obliquely acquired photos have been used to create a digital 3D model of the STM of the Eiger North Face which is in the collection of the Institute for Cartography at TU Dresden. The blue polygons denote the locations from which the photographs were taken. The ‘dome’ shape of the array is ideal but not absolutely necessary for SfM reconstruction - compare with Figures 5.12, 5.13, and 5.14 in Section 5.2.2.

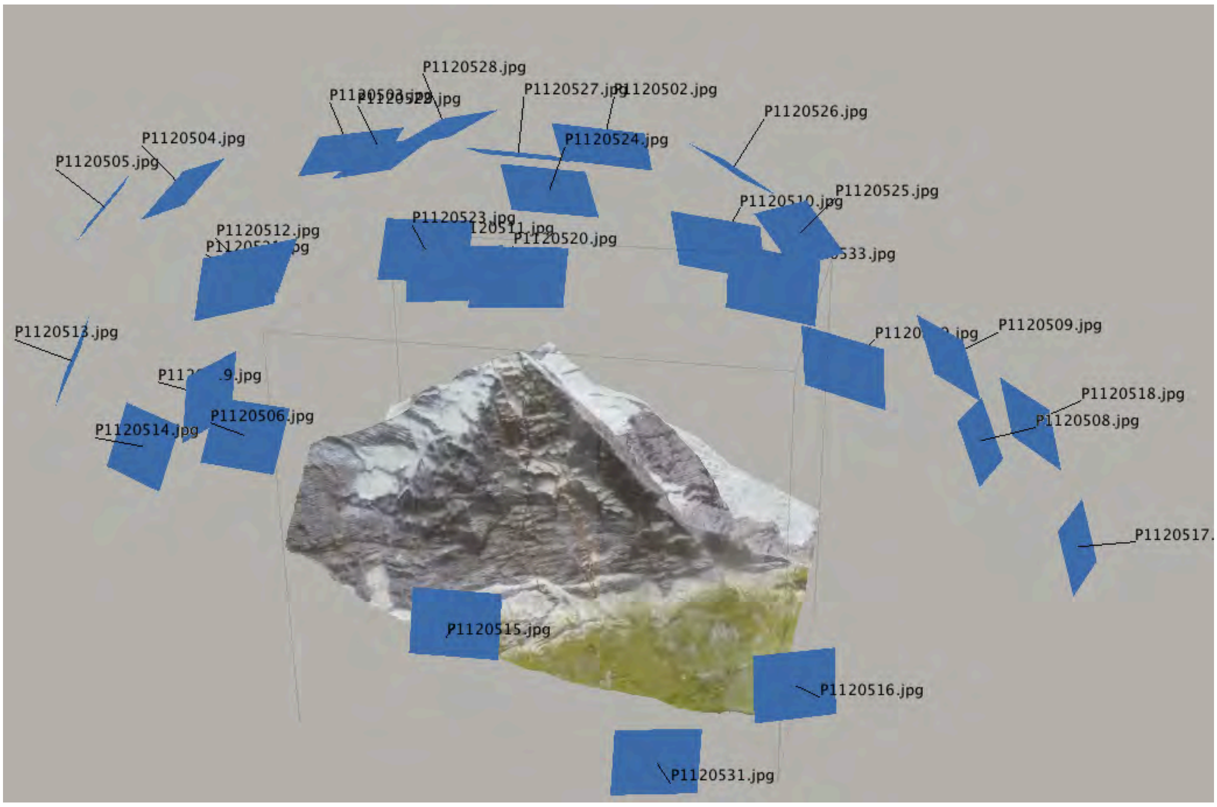


Figure 2.6 Example of SfM photo array and reconstructed digital 3D model of the Eiger STM.

SfM is only just beginning to be recognized as a useful tool for cartography. Creation of DEMs from aerial imagery without laserscanning is one of the possible uses. As stated by Vogiatzis and Hernández (2010), “Recovering 3D shape from photographic images is an efficient, cost effective way to generate accurate 3D scans of objects.”

Source: sac.ledifluh.ch

3 CASE STUDY: DACHSTEIN, AUSTRIA

To test the methods discussed so far in this study, it was decided to produce two examples of autostereoscopic 3D displays using different materials and processes. Before research could begin, a suitable location had to be chosen. After considering various sites, some as distant as the Kailash in Tibet, the Dachstein Massif in Austria was selected as the test area.

Situated on the borders of the states of Styria, Upper Austria, and Salzburg, the Dachstein is a good subject to test the capabilities of the methods used in this study. The mountain itself has rugged topography with many vertical or nearly vertical faces and even some overhanging areas which are impossible to reconstruct from raster-based DEMs. The area surrounding the mountain has a variety of terrain for comparative purposes. The availability of LiDAR data and aerial imagery, both nadir and oblique, was the final determining factor.

Two test projects were initially chosen to combine different data sources, methods of generating 3D digital models, and mode of presentation. The first was to use aerial imagery and SfM to generate a TIN which would then be converted to CNC milling commands to make an STM. The second was to use LiDAR scans to generate a textured digital model which would then be depicted in an LFD. The combination of a digital source model and a physical output for display is designated as a **hybrid method** in this study.

3.1 HYBRID METHODS

These models can then be used to generate solid terrain models or other autostereoscopic displays using digital technologies such as CNC milling, stereolithography, or lenticular Foil.

For an LFD, using a 3D digital model as the source for the images allows for complete control over the presentation of the subject. This control can result in a better result; for example, the depiction of the image is not limited by the conditions present at the site at the time of image acquisition.

For an STM, traditional construction methods provide excellent results, but are time consuming and labor intensive, resulting in high costs of production. Since SfM can use oblique photographs, this problem is overcome

With the development in recent years of CNC milling and also the availability of DTMs, it is now possible to do much of the work of creating a solid landscape model by mechanical means with greater economy in both time and cost. Human skill is used in data preparation before milling, and the final carving and coloring of the landscape– the 'art' of the model. “Do not give away the most creative work to machines” (Mair 2012).

Following are three basic methods to create a solid landscape model from a DTM using CNC (from Welter 2013):

1. Milling directly to the profile defined by the DTM

The most straightforward approach, it involves programming the CNC machine to simply follow the profile of the landscape as defined by the DTM. Tests should be performed to determine the most suitable combination of material to be carved, cutting head, and depth of pass to achieve satisfactory results.

This method has been used successfully, for example, to create a relief of the Elbe Valley for a multimedia installation at the Stadtmuseum Dresden (Hahmann et. al. 2009) (Figure 3.1). But while the combination of DTMs and CNC works relatively well in low-relief landscapes, for depicting mountainous areas (high relief) it suffers from the same disadvantage as stereolithography: Lack of detail on vertical or near vertical surfaces.

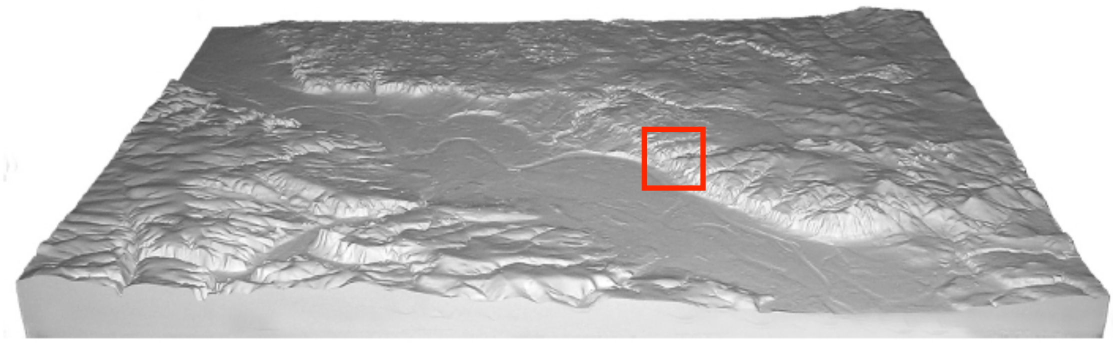


Figure 3.1 Low relief STM (from Hahmann 2006) Inset: see Figure 3.2

2. Milling to the profile of an 'eroded' DTM and then cover the resultant core with a layer of material for detail carving

A method suggested by Toni Mair in the book Das Landschaftsrelief: Symbiose von Wissenschaft und Kunsthandwerke (2006) is to mill the core of the relief model using CNC (Figure 3.2) and carve the landscape details into the layer of material covering the core for that purpose . This would permit detailing of vertical surfaces. To allow for the thickness of the modeling layer, the profile of the DTM must be 'eroded', a technique borrowed from digital image processing.

This method has the disadvantage that in the process of eroding the DTM, the original profile is lost. While it should be regained with the application of the modeling layer, the accuracy depends entirely on the skill of the builder in maintaining a constant thickness of the applied material. This can be challenging, and is in any case time consuming as many thickness measurements must be made during the application process, slowing the overall progress and reducing the economy of time. And if the modeling layer is not applied with due care, the profile of the landscape is altered and the accuracy of the model is compromised.

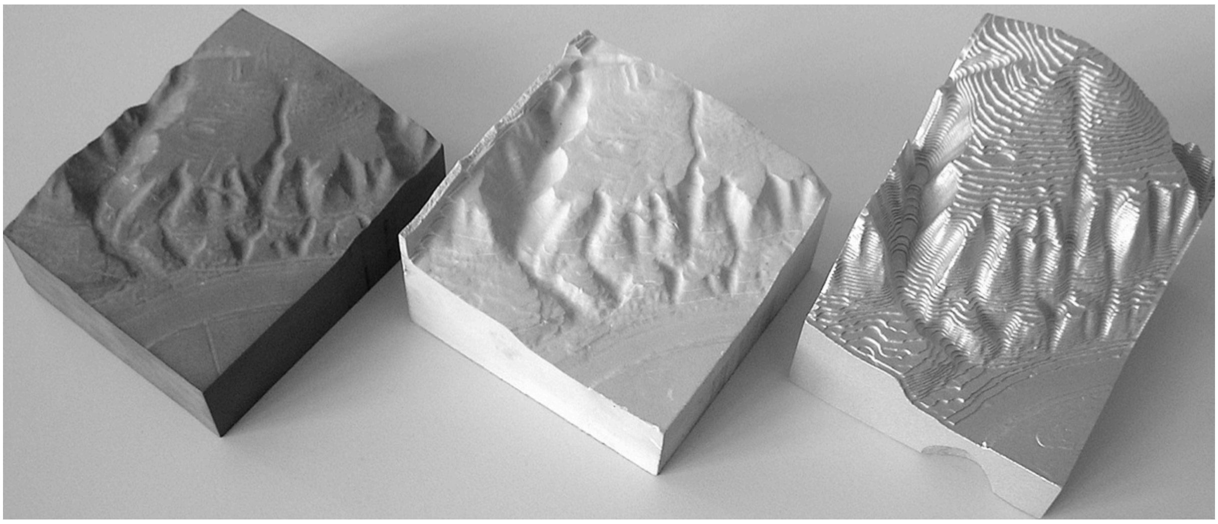


Figure 3.2 Examples from CNC milling tests (from Hahmann 2006) See Figure 3.1

3. Milling the 'negative' of the DTM to create a mold from which a 'positive' will be cast of the material to be carved

Some traditional relief builders, instead of making a positive step model to use as a core, make a negative step model (Figure 4.1) to create a mold from which a positive form is cast in plaster. In this instance, instead of cutting 'outside' the contour lines resulting in layers which are stacked to form the basic shape of the model, the cuts in the material are made 'inside' the contour lines creating layers which define the negative space. This method reduces the time and cost of creating a landscape model by eliminating the need to make a separate mold, but requires much visualization skill on the part of the builder.

4 PROJECT 1: NEGATIVE MOLD USING CNC MILLING

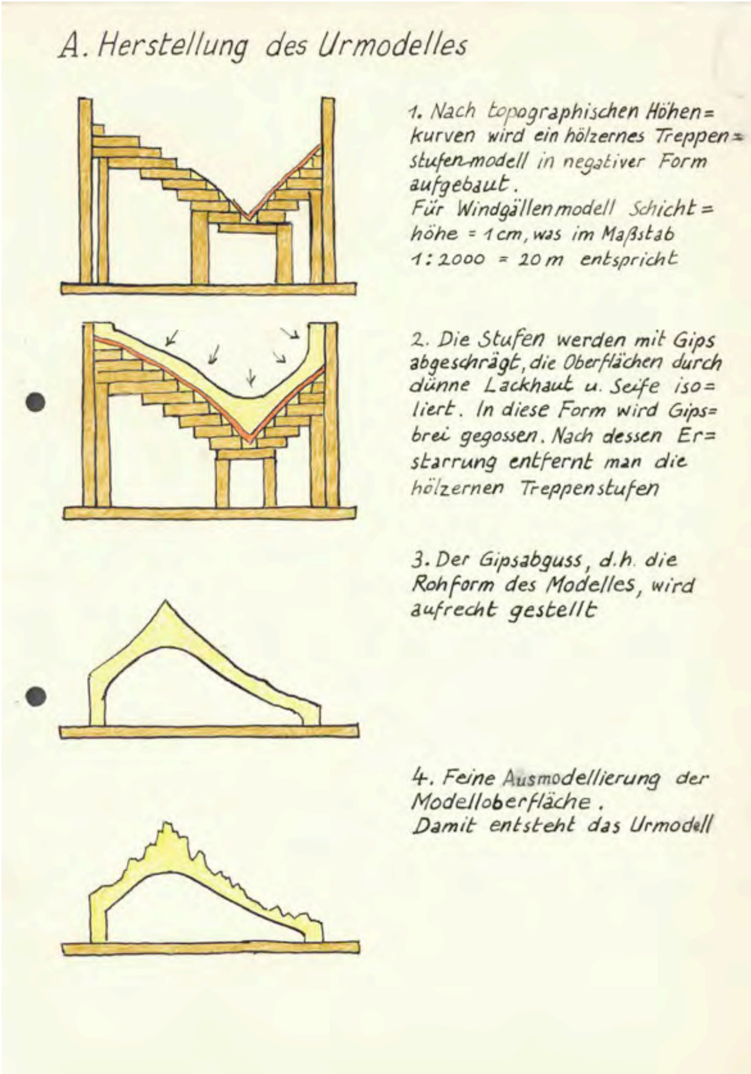
Räber and Hurni (2008) suggested "the relief making process ideally starts with an automatically carved negative form of the relief model." This proposed process for creating a negative step model (Figure 4.1) builds upon the work of Eduard Imhof, founder of the Institute for Cartography at ETH Zürich, whose process of creating a negative mold is shown in Figure 4.2 (translated from German by the author).

For the project in this study, a 3D digital model was generated from aerial photographs using SfM to create a DSM. By inverting the DSM and converting to CNC command codes, a negative mold was to be milled.

From that mold, positive copies would be cast in a carvable material. These copies would then be finished by hand-carving and coloring to match photographs of the actual terrain, thereby combining traditional and modern methods to produce a lower cost model that retains the quality of artisanal work.

Figure 4.1 Negative step model (from Mair 2012)

Figure 4.2 Imhof's method for casting a model from a negative step mold



Production of the prototype model

1. **According to topographical contours, a wooden step model is built up in a negative way. For the Wingällen model, the layer height = 1 cm, which, at a scale of 1:2000, corresponds to 20 m.**
2. **The steps will be smoothed with plaster; isolate the surfaces by painting with a thin skin of lacquer and soap. Gypsum slurry is poured into this form.**
3. **After its solidification, remove the wooden steps. The plaster cast, i.e. the raw form of the model, is placed upright.**
4. **Fine modeling on the outer surface of the model. Thus, the prototype model is created.**

Source: www.library.ethz.ch (translated from German by the author)

4.1.1 Creation of a Negative Digital 3D Model

A DSM of a portion of the Dachstein Massif was generated using Structure from Motion (SfM). The process will be discussed in detail in Section 5.2.3 below.

Aerial imagery was acquired from the Austrian Federal Office for Calibration and Measurement (Bundesamt für Eich- und Vermessung; BEV). These are conventional nadir view photos taken in 2010. Using the provided reference map showing the locations of the center of each image (Figure 4.3), a block of ten photos was selected covering the area to be modeled: 4764-4768, and 4799-4803 (example in Figure 4.4). The photos have a 60% overlap along the direction of the flight path, and a 30% sidelap from one flight path to the next. This proved to be adequate coverage for SfM reconstruction.

Since the model was intended for use in making a mold using CNC milling, the loss of some information on the vertical faces due to the use of nadir aerial photos was not an issue. The detail on the surface of the mold itself must necessarily be simplified because of the requirements of the casting process.

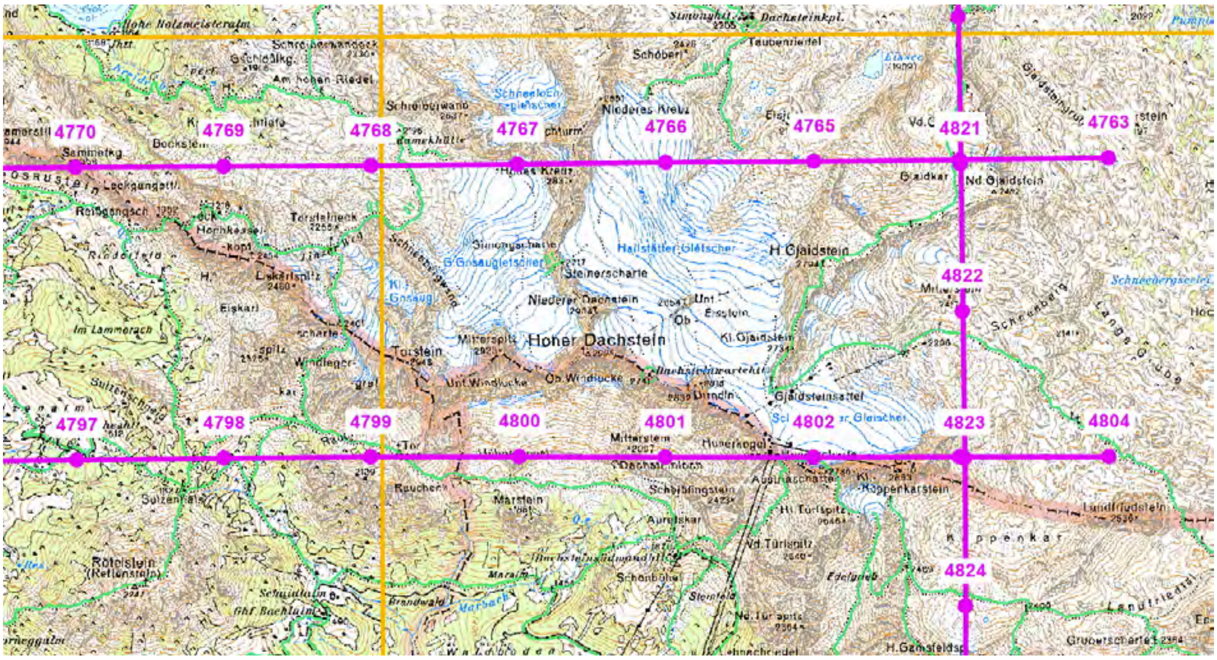


Figure 4.3 Reference map of aerial imagery in the Dachstein region   Source: BEV

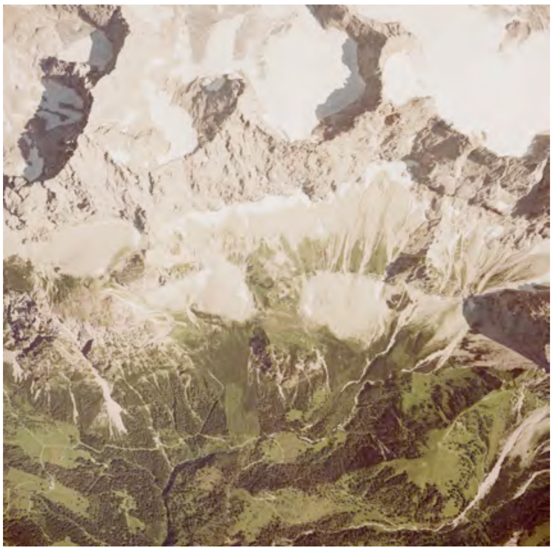


Figure 4.4 Nadir aerial photo of the Dachstein (#4800 – see Figure 4.3)   Source: BEV

Prior to loading into PhotoScan software for SfM processing, the photos required cropping to eliminate the fiducial marks. If this is not done, the image matching algorithms of SfM attempt to match pixels that are contained in the image (fiducial marks) but not on the surface, creating artifacts that distort the geometry of the generated TIN. The minimum area possible was removed, and the resultant overlap between photos was still adequate for an accurate reconstruction (Figure 4.5).

Figure 4.5 Dachstein Massif reconstructed with SfM using nadir photos

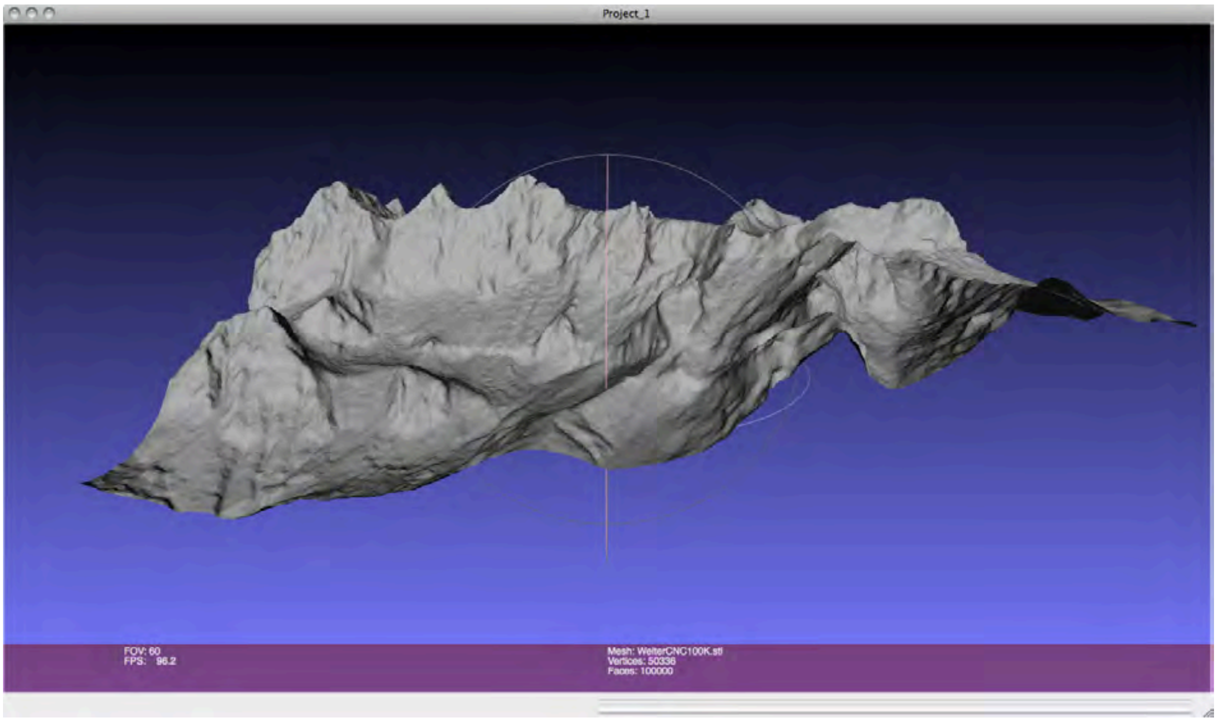


Figure 4.6 Visualization of Digital Surface Model (DSM) in Meshlab

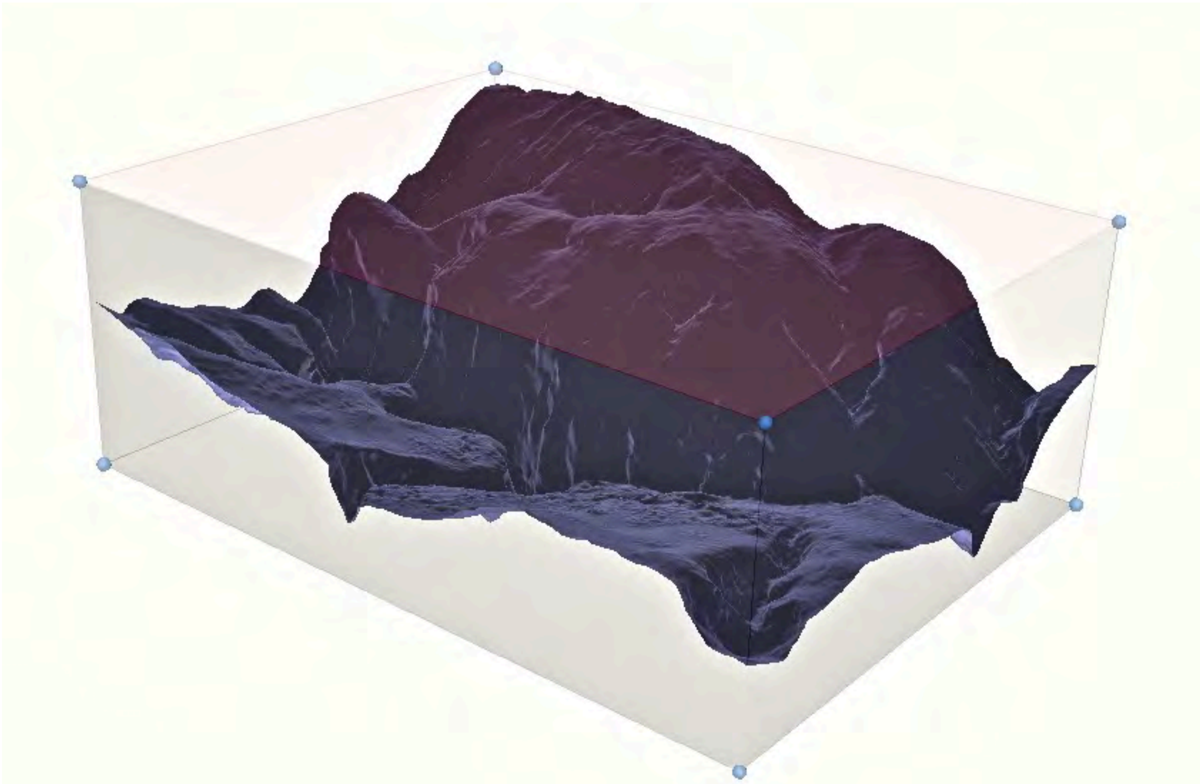


Figure 4.7 Inverted DSM prior to inversion of the “normals"

The mesh (TIN) was exported to Meshlab software. It was visualized as a surface (Figure 4.6) and then the surface was ‘inverted’ by inverting the ‘normals’; changing the designation of the ‘outside’ and ‘inside’ faces of the triangles in the mesh relative to the observer (Figure 4.7). Once this is completed, the file was exported in the .stl format. Files in the .stl format are converted to machine commands by the proprietary software of the CNC machine.

4.1.2 Milling the Mold

Arrangements were made with the Laboratory and Field Test Network (Labor- und Versuchsfeldverbund Zeunerbau; LVV-ZEU) of the Faculty of Mechanical Engineering at TU Dresden to do the CNC milling of the mold. The .stl file was sent and inspected. A couple of minor changes were made to meet the capabilities of the machine and a size error was corrected.

Because the mold was to only for making a low number of plaster casts, the material chosen was a lightweight extruded polystyrene. This material is strong and rigid enough for the casting process, yet relatively soft and easy for the the CNC machine to cut. Material can be removed at a greater depth per pass, reducing the machine time required and therefore the cost of the milling. Also, this can reduce the overall timeframe of a project.

Unfortunately due to circumstances involving the flooding of the Elbe River in Dresden during June 2013, there were extensive delays in the production schedule of LVV-ZEU. As of this writing, the project is still proceeding and efforts are being made toward its completion.

Lacking imagery of the actual project at this stage, photos from Hahmann (2006) have been substituted in Figures 4.8 and 4.9 to illustrate the milling process.

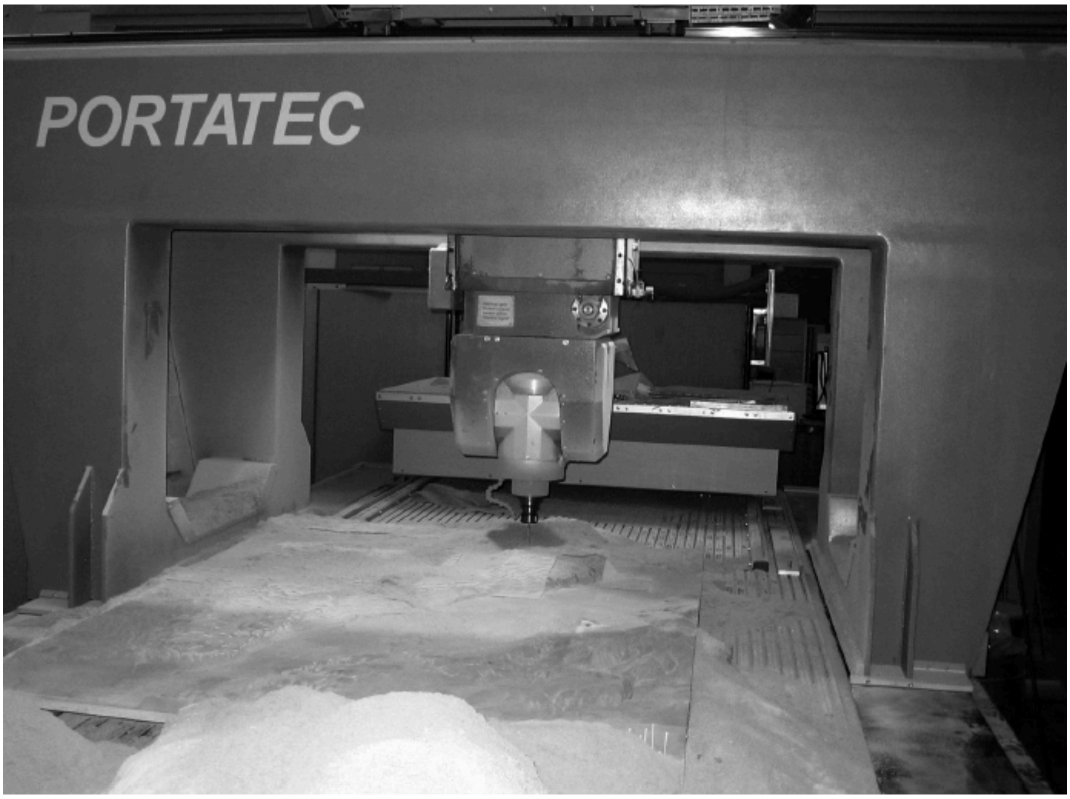


Figure 4.8 Creating an STM with a CNC milling machine

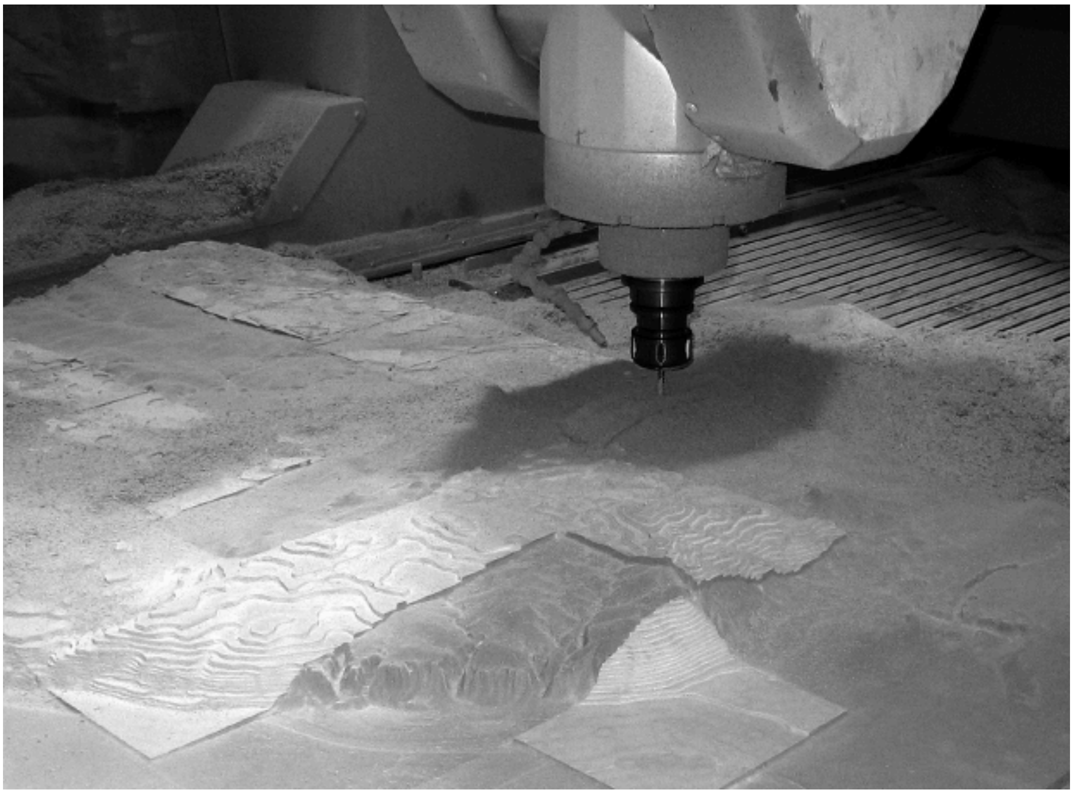


Figure 4.9 Milling contours in low-relief terrain

Source (both figures): Hahmann 2006

5 PROJECT 2: LENTICULAR FOIL DISPLAY FROM A DIGITAL 3D MODEL

For lenticular foil display, an entirely different approach is used. A digital model is created as in the other methods, but since appearance is important as well as shape, ‘texture’ must be applied i.e the model must be ‘draped’ with the photographs. The quality of the texture is determined by the parameters of the ‘texture map’, not the resolution of the original photos.

Once the digital model is created, it is opened in 3D modeling software and multiple overlapping images of the model are taken using the software’s virtual camera. Lighting, view angle, aspect, and position are all controllable to a degree not usually possible in the ‘real’ world.

The concept for this project was to make a large make an oblique digital model from LiDAR data and present it in a large-format (2.5 x 6 m) LFD. A artist’s concept of the envisioned display was created from a view taken in Google Earth (Figure 5.1). The Dachstein Südwand (South Face) was selected not only for its topography, containing the slopes with the most vertical faces but also for its recognizability, being the view of the mountain seen by most visitors to the region.

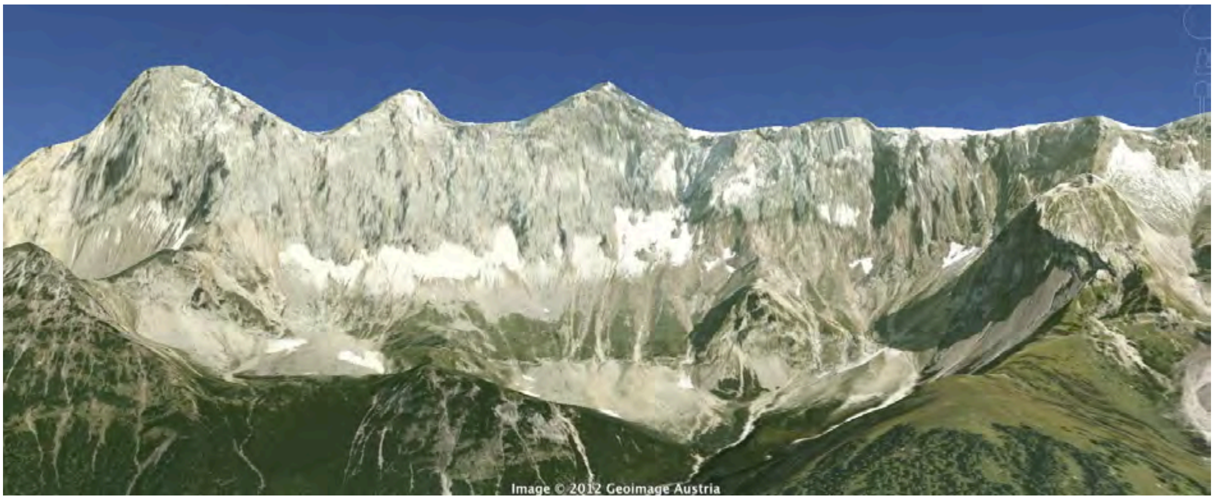


Figure 5.1 Artist’s concept of the large format LFD of the Dachstein Südwand

Source: facility.unavco.org

5.1 GENERATING A 3D MODEL FROM LASERSCAN DATA

TLS data of the Dachstein Südwand was provided by the Institute for Cartography at TU Dresden. The data was acquired in 2010 and 2011 by a team headed by Manfred Buchroithner using Riegl laserscanning equipment (Buchroithner et. al. 2013).

Since the scans were taken obliquely from a terrestrial vantage point, it was thought that this would produce the optimum results. This was based on the hypothesis that the point-of-view of the viewer of the would approximately match that of the scanner location relative to the scene depicted in the LFD. At the same time as the scans were acquired, photographs were taken for the purpose of texturing a digital 3D model.

The point cloud was visualized as a surface using the InstantPlayer feature of the InstantReality software framework (www.instantreality.org). The results initially were promising: good resolution, accurate reproduction of topography including the large overhanging area on the Hoher Dachstein peak. It was thought that all that would need to be done was the addition of the texture and the model would be complete and ready to be exported to a 3D modeling program for the creation of stereomate images.

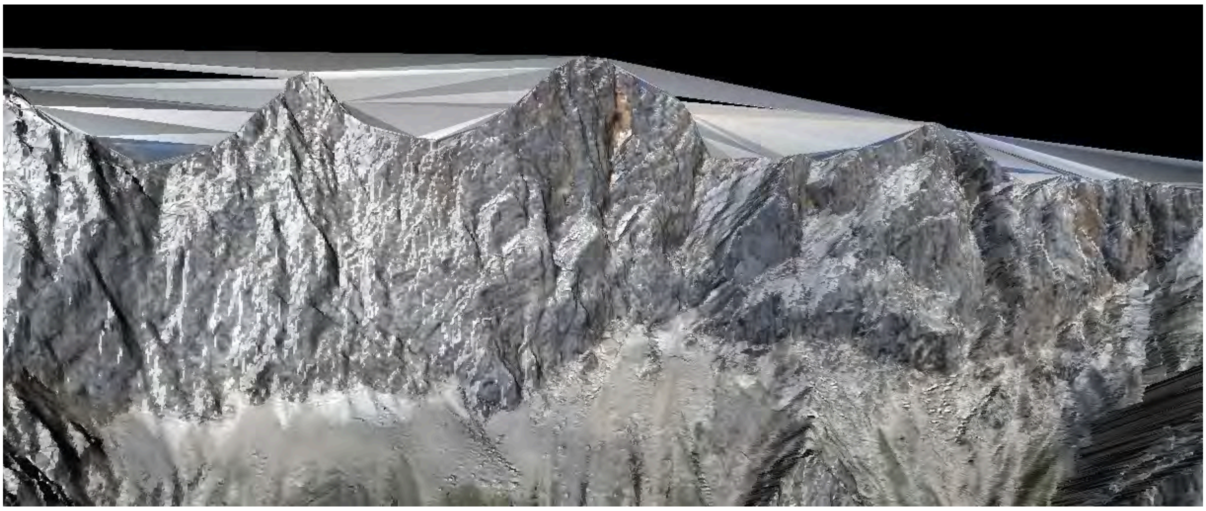


Figure 5.2 Visualization of TLS point cloud as a surface with vertex colors - front view

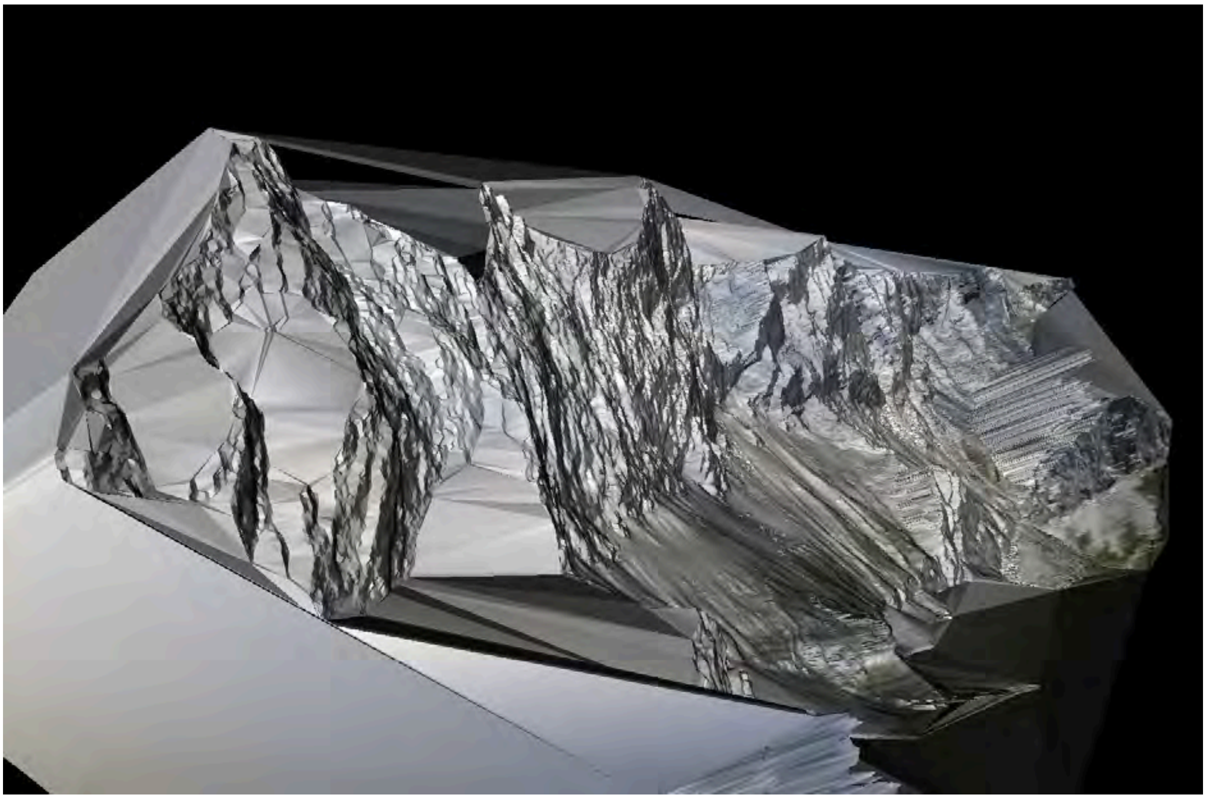


Figure 5.3 Visualization of TLS point cloud as a surface with vertex colors - side view

5.1.1 Difficulties

As seen in Figure 5.3, viewing the 3D model from the approximate aspect of the scanner results in a satisfactory view and compares favorably with the desired final depiction, as envisioned in the mock-up image. However, when viewed from the side, a shortcoming in this method was noticed (Figure 5.4).

Laserscanning from a terrestrial position resulted in large ‘shadow’ areas where no information of the topography was captured behind foreground hills and outcroppings. At first, this was not considered a problem. The positions of the virtual cameras taking the stereomate images could be set so the problem areas would not be visible in the final LFD.

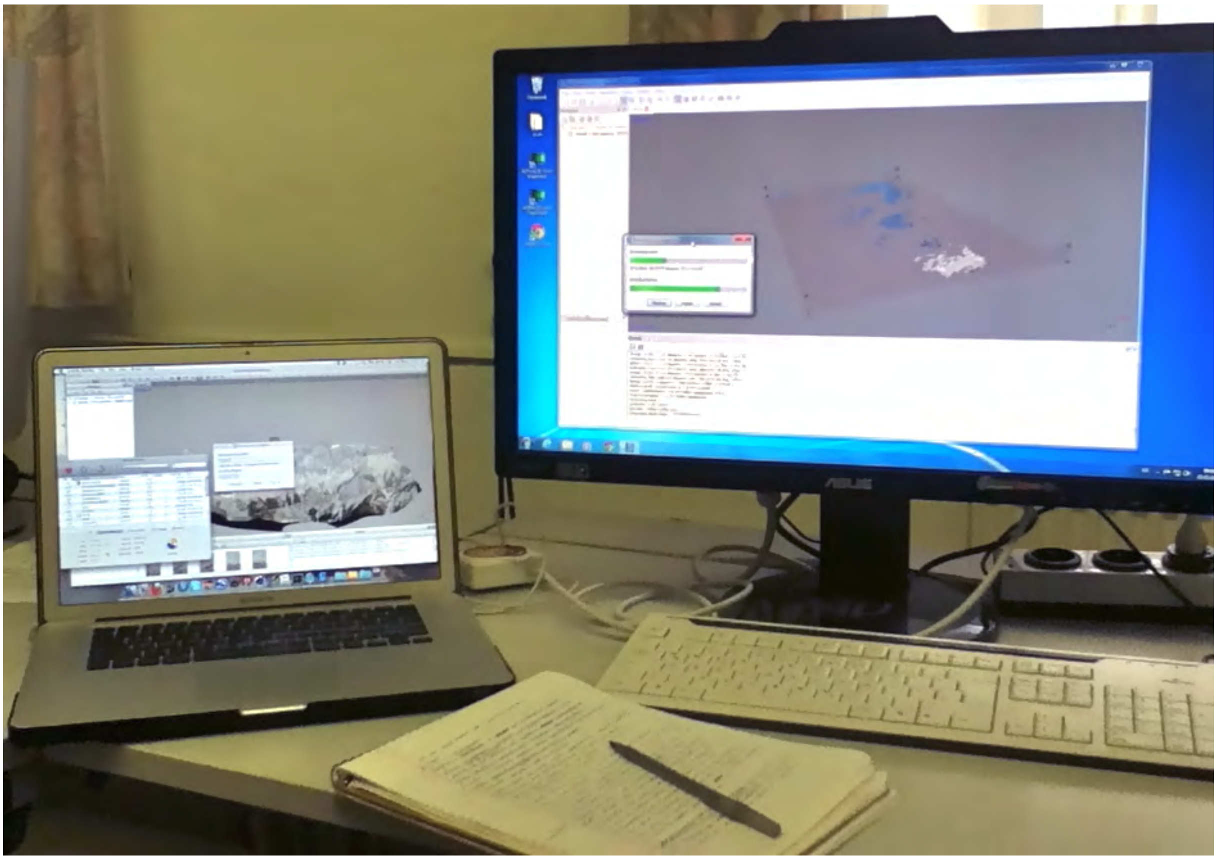
A more difficult problem arose when it was attempted to add texture to the model. Photographs taken from the position of the scanner at the time of scanning were too small and low-resolution to be useful for adding the texture to the model.

It was suggested by Prof. Dr. Manfred Buchroithner that oblique aerial photos taken by Klaus Habermann in 2005 and available at the Institute, might be used to texture the model.

Many attempts were made to accomplish this. It was proposed to merge the TLS-based mesh with an ALS-based mesh to ‘fill in’ the obscured areas. This proved not to be practical. Assistance was solicited to try to solve the problem, but all solutions were ultimately unsuccessful.

Matching the laserscanning data captured on a particular date and vantage point with the texture photos captured on a different date and vantage point proved to be more difficult than anticipated. Matching points on in the scans with points in the photos was nearly impossible. Also, the geometry of the TIN would have to be altered manually

Due to the aforementioned difficulties, a different methodology was sought.



Source: author

5.2 GENERATING A 3D MODEL USING STRUCTURE FROM MOTION

In July 2012, the author attended the Aerial Archaeology Training School conducted in Mérida, Spain. One of the methods used during the course to create 3D models to document excavation sites was SfM. Students received training using PhotoScan. Photographs were taken in the field and brought back to the computer lab and 3D digital models were created. The results were impressive.

Because of this experience, it was decided to try SfM for this project. A set of oblique aerial photographs was already in use; it was a simple matter to load them into PhotoScan and compare the results. Initial results were so promising that all research effort toward creating digital 3D models was shifted to SfM.

5.2.1 Image Acquisition

The images used for the reconstruction were acquired by Thomas Kunzelmann in October, 2005. The camera was mounted to the dashboard of an aircraft and several flybys of the Dachstein Südwand were made (Figures 5.4, 5.5, and 5.6). Technical issues with the camera resulted in unusable photos from some of the flybys, but on three passes the images were in focus, resulting in a sufficient number of usable photos for 3D reconstruction of the terrain.

Figure 5.4 Camera mounted in aircraft

Figure 5.5 Image acquisition

Source (both photos): T. Kunzelmann (taken 2005)

Figure 5.6 Oblique aerial photo of the Hoher Dachstein peak Source: T. Kunzelmann

5.2.2 Software Comparison

Before proceeding, a comparison was made of three commonly used SfM software packages: Autodesk 123D Catch (freeware), VisualSfM (freeware), and PhotoScan (commercial). After only a few test reconstructions it became readily apparent that PhotoScan produced the best results and so was chosen for this project. A detailed technical comparison of the three softwares is presented in Ehlert (2013).

5.2.3 Workflow Steps

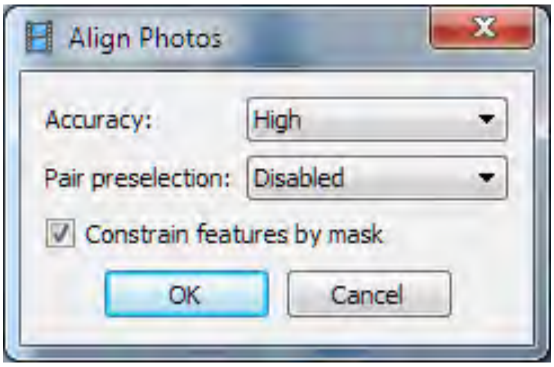
The workflow to generate digital 3D models with SfM using PhotoScan is simple and straightforward, consisting of five basic steps:

1. ***Import Photos***
2. ***Align Photos***
3. ***Build Geometry***
4. ***Build Texture***
5. ***Export Model***

There are also some optional intermediate steps for checking quality or making adjustments. These will be described in the text at the appropriate place.

The workflow will now be discussed as it was utilized in the course of this project. The technical information about PhotoScan in this section is adapted from Verhoeven 2011. Additional information is from Agisoft LLC 2013a and screenshot imagery from Agisoft LLC 2013b.

1. ***Import Photos* -** Thirty nine photos from the Kunzelmann flight were selected for use in the reconstruction and imported (Figure 42). Photos were in the TIFF format and each file was approximately 40MB in size. PhotoScan can import photos in JPEG, TIFF, PNG, BMP, or MPO formats.



2. ***Align Photos* -** In this step, SfM algorithms detect and match image feature points, locate those feature points in space, and render the points as a sparse three-dimensional point cloud. (Figure 5.7). At this step in PhotoScan, the degree of accuracy can be chosen. This has an effect on the amount of computer effort required and the rendering time: low accuracy = faster rendering, high accuracy = slower rendering.

A masking feature allows the elimination of background portions of the image which may adversely affect the geometry of the model. These points can be seen as outliers in the point cloud and will otherwise need to be removed manually using a bounding box before building the geometry (Figure 5.8).

Use of this feature also reduces the number of calculations required by reducing the number of feature points needing to be mapped and having a positive effect on the amount of computer memory and processing capacity needed.

For the Dachstein model, background points (blue) and points of peaks behind the Südwand (gray) were also matched by the algorithm. A bounding box delimiting the finished model was established, and outlier points were also chosen and deleted manually.

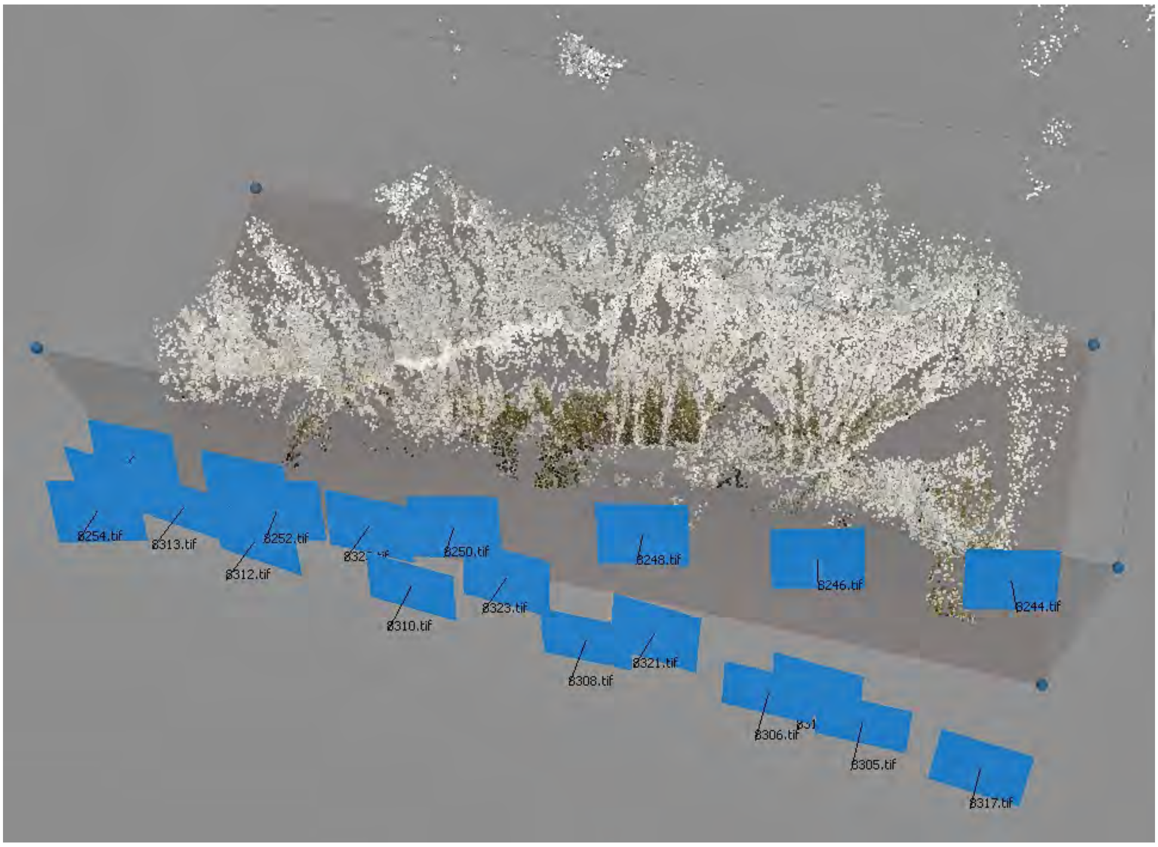


Figure 5.7 *Align Photos* – Point cloud showing photo locations

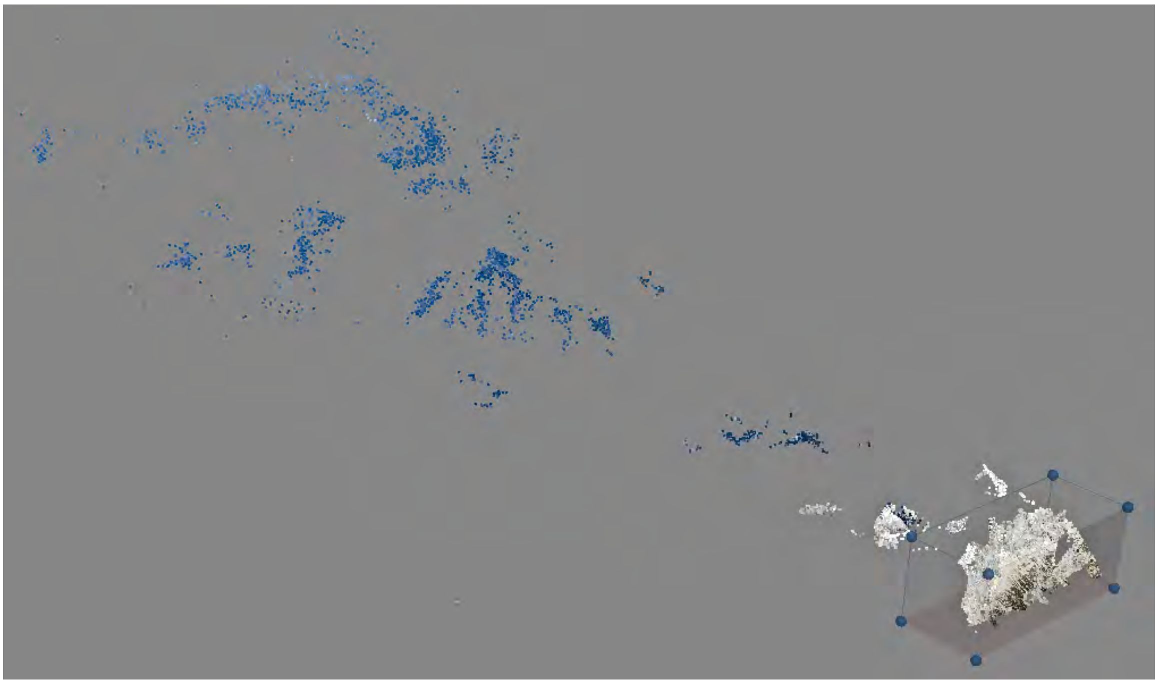
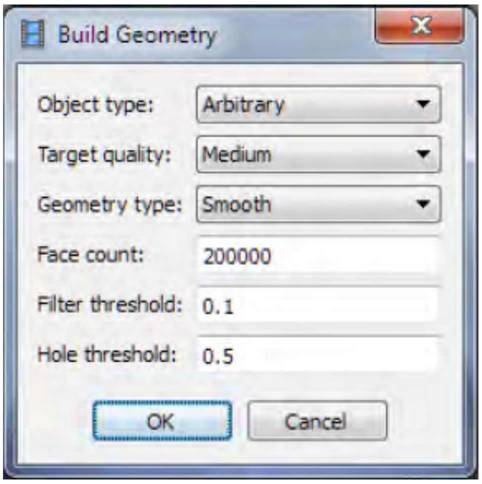


Figure 5.8 *Align Photos* – Point cloud showing outliers and bounding box

3. ***Build Geometry* -** Next, geometric scene details are built by applying a dense, multiview stereo-reconstruction to the aligned image set, and the result visualized as a mesh (Verhoeven 2011).



Options of ***Object type***, ***Target quality***, and ***Geometry type*** can all be specified in relation to the parameters of the desired results. ***Smooth*** geometry suffices for most purposes. ***Exact*** (option not shown) geometry is used when accuracy is the prime factor. The ***Height Field*** (option not shown) geometry is designed specifically to produce optimal results when used with nadir aerial imagery.

Similarly to the ***Accuracy*** setting when aligning photos, the ***Target quality*** setting greatly affects the computational effort required; each successive level of quality comes with a penalty of an <u>eight times</u> longer processing time!

Specifying the ***Face count*** limits the number of triangles in the mesh, which is another way to reduce the computational effort required.

Upon completion of the build process, the completed mesh can be visualized as a mesh, a surface, or a surface with vertex colors (Figures 5.9, 5.10, 5.11).

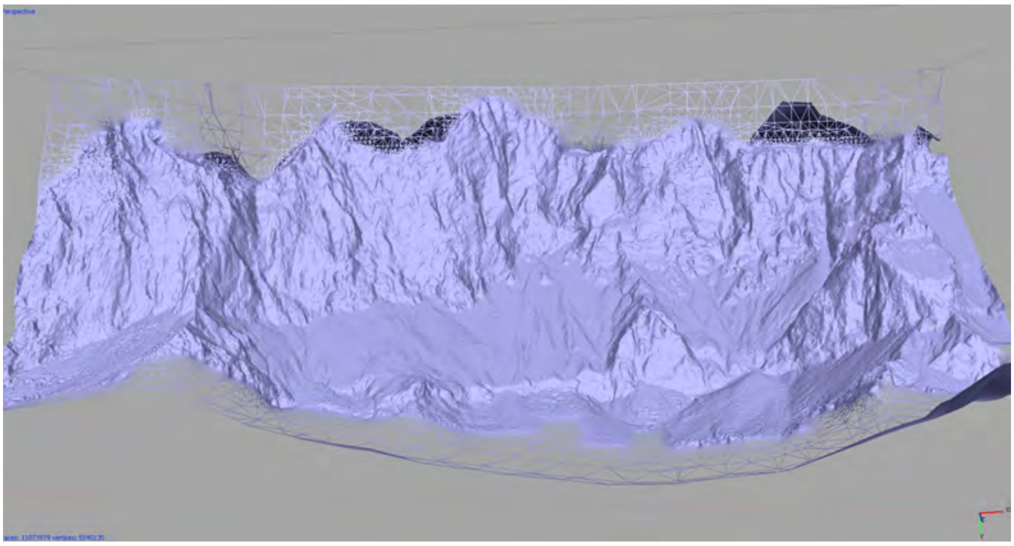


Figure 5.9 *Build Geometry* – Mesh

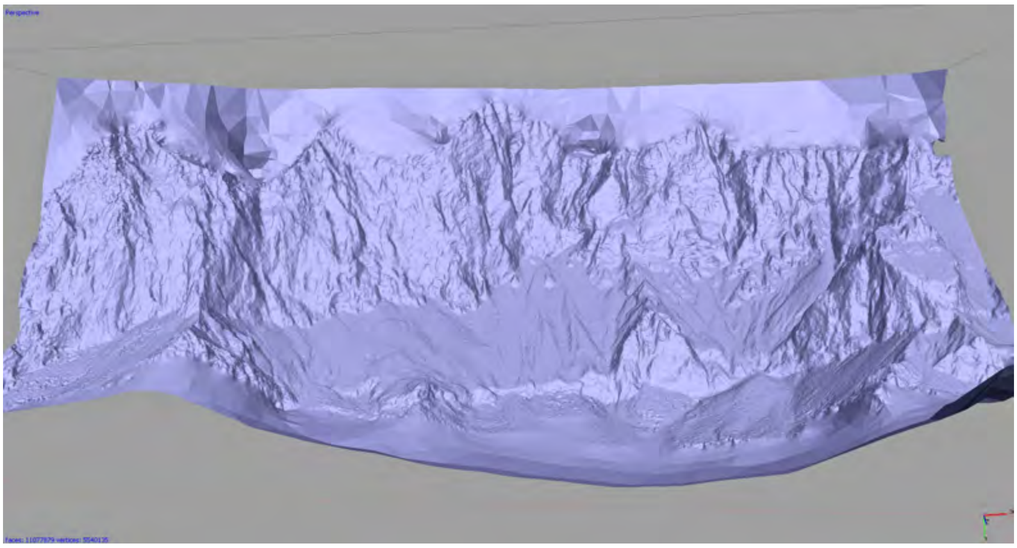


Figure 5.10 *Build Geometry* – Surface

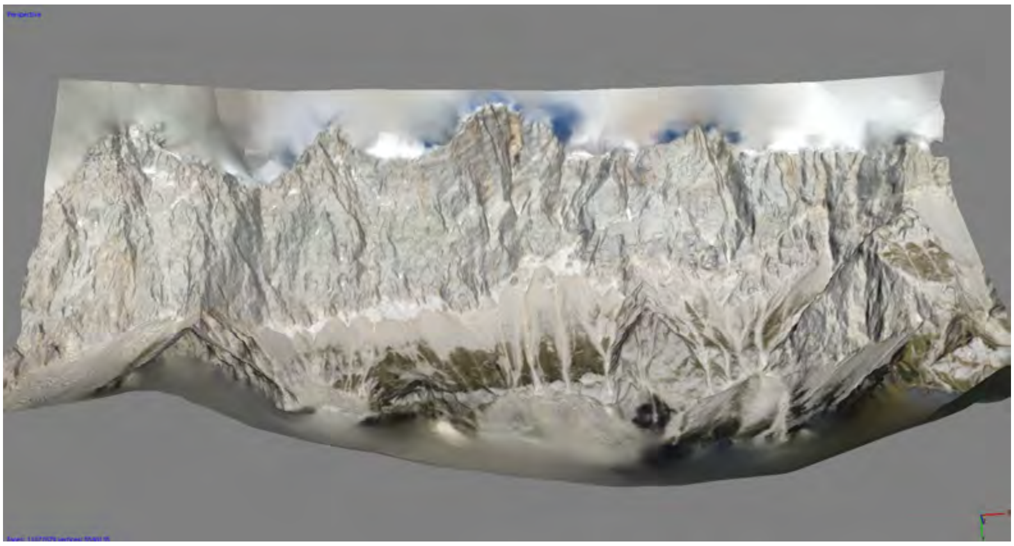
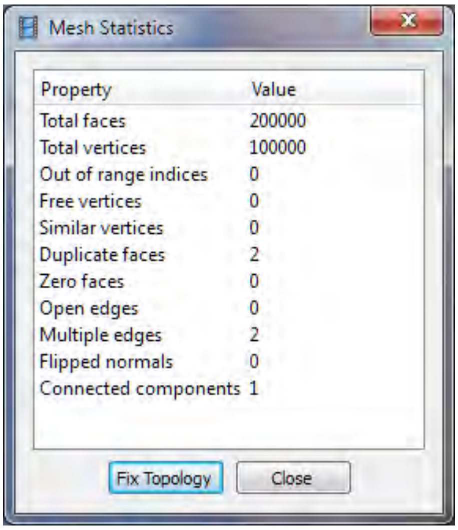


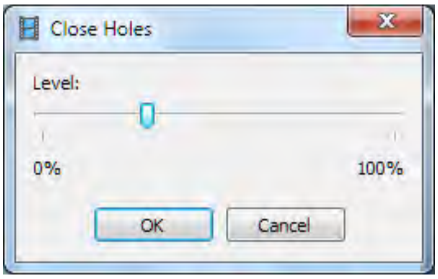
Figure 5.11 *Build Geometry* – Surface with vertex colors

Since the photos used were taken from only one side of the mountain, the geometry included only the ‘faces’ of the peaks, resulting and a connecting mesh along the ridge line. These sections of the mesh were eliminated by selecting and deleting triangles manually, a time-consuming process. More complete photo coverage of the subject terrain would make this additional step unnecessary.

An intermediate step which can be performed at this point is a check of the ***Mesh Statistics*** for errors such as duplicate faces, open edges, flipped normals, etc. While not critical in this instance, if the model is to be used for CNC milling or 3D printing, these errors must be repaired before the file can be converted to machine commands. The ***Fix Topology*** function performs an automatic repair on the mesh.

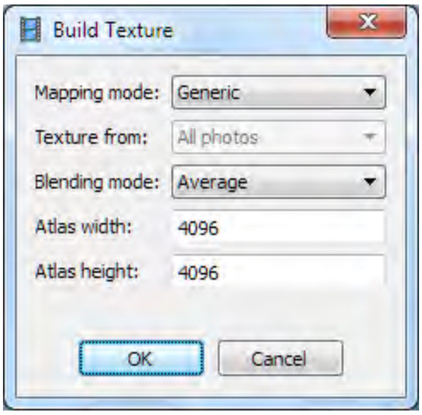


Also at this point, the ***Close Holes*** function should be used. This is another repair process for the mesh. The size of the holes to be filled can be set. Again, this is not important for the LFD, but is important for CNC or FDM.



Another optional function is in the menu under ***Tools*** > ***Decimate Mesh***. PhotoScan by nature of its algorithms tends to create more highly-dense meshes than is necessary for most applications. By decimating the mesh, the total number of triangles in the mesh is reduced to a manageable level.

4. *Build Texture* - Once the geometry is built and the mesh is refined or repaired, the next step is to ***Build Texture*** (Figure 5.12). This step only affects the visual appearance of the model and is not necessary if the model is to be used for CNC or FDM purposes.



The previously aligned photographs are now merged and draped onto the mesh, giving it a highly realistic appearance. ***Mapping mode*** determines the procedure for locating the texture on the mesh, Blending mode controls the merging of the images, and ***Atlas width*** and ***Atlas height*** refer to the resolution of the texture itself. This will be discussed more in Section 5.2.4.

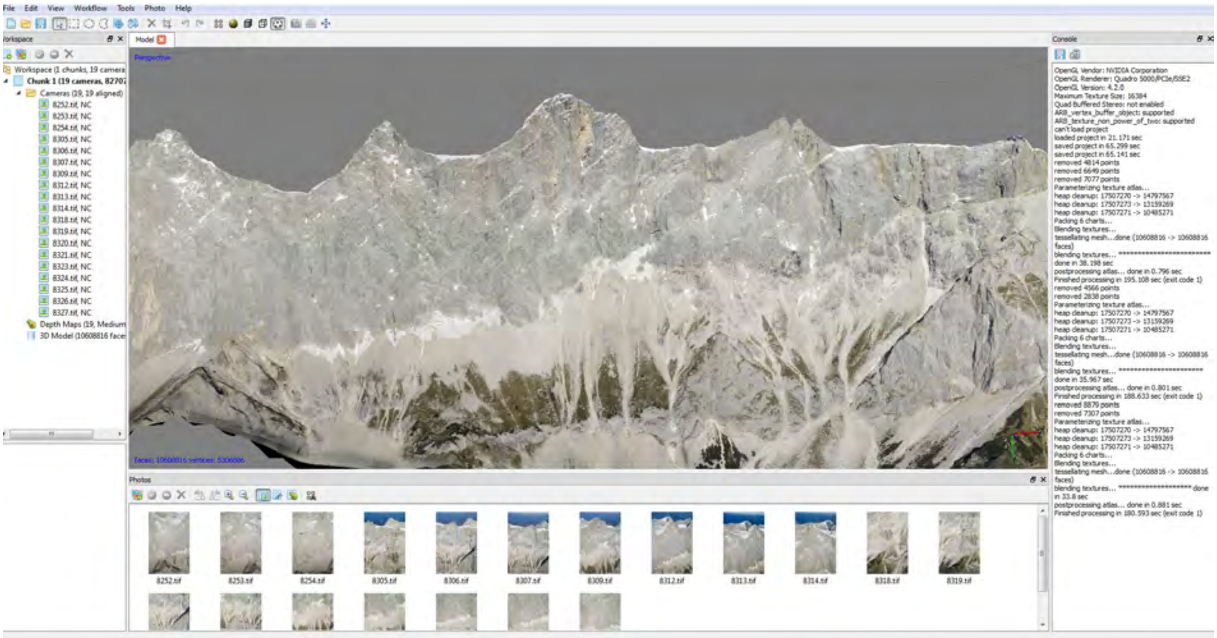


Figure 5.12 *Build Texture* – Textured model showing source photos

5. *Export Model* - PhotoScan supports exporting models in many formats used by 3D modeling and animation software including: obj, fbx, ply, wrl, pdf, and others. The PDF option embeds the 3D model into an interactive PDF, viewable by anyone with Adobe Acrobat software. This is a very useful method for sending and demonstrating digital 3D models.

For the Dachstein LFD project, the model was exported in .fbx format for visualization in 3D Studio Max software.

Figures 5.13 - 5.16 show the sequence of steps in the workflow using the final version of the Dachstein model.

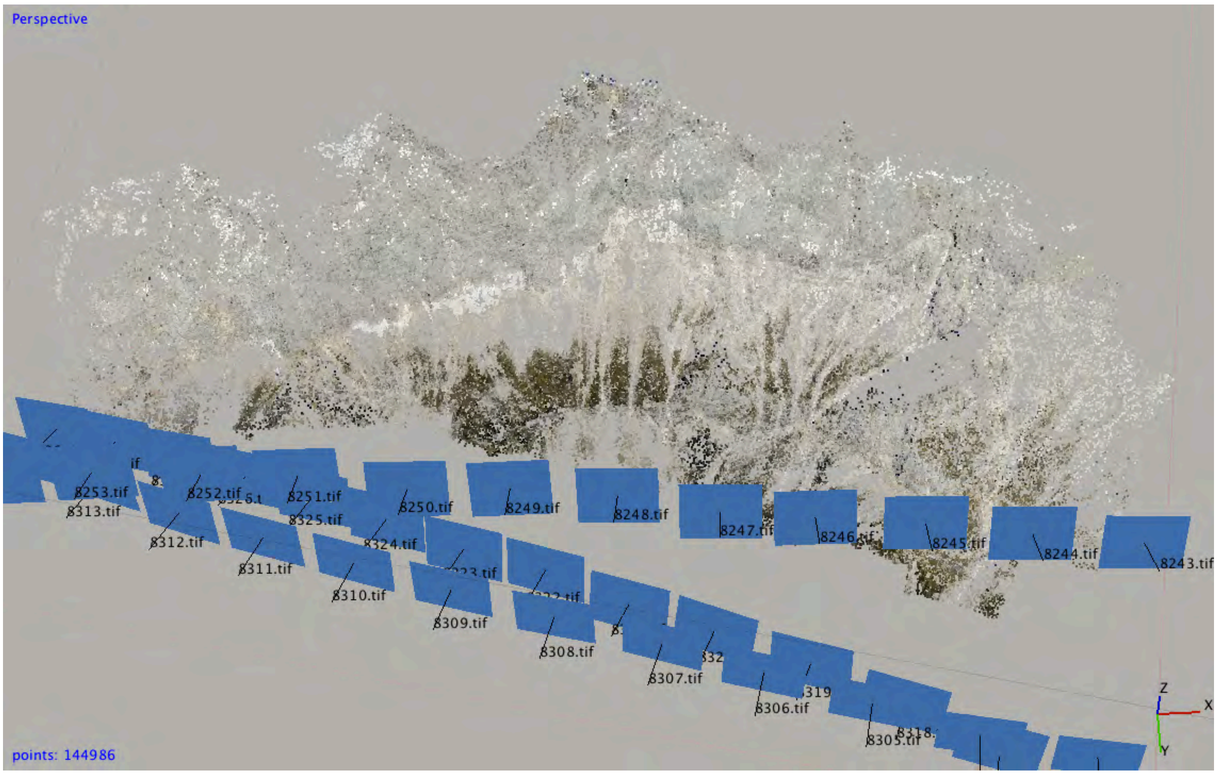


Figure 5.13 Dachstein – Point cloud with photo array

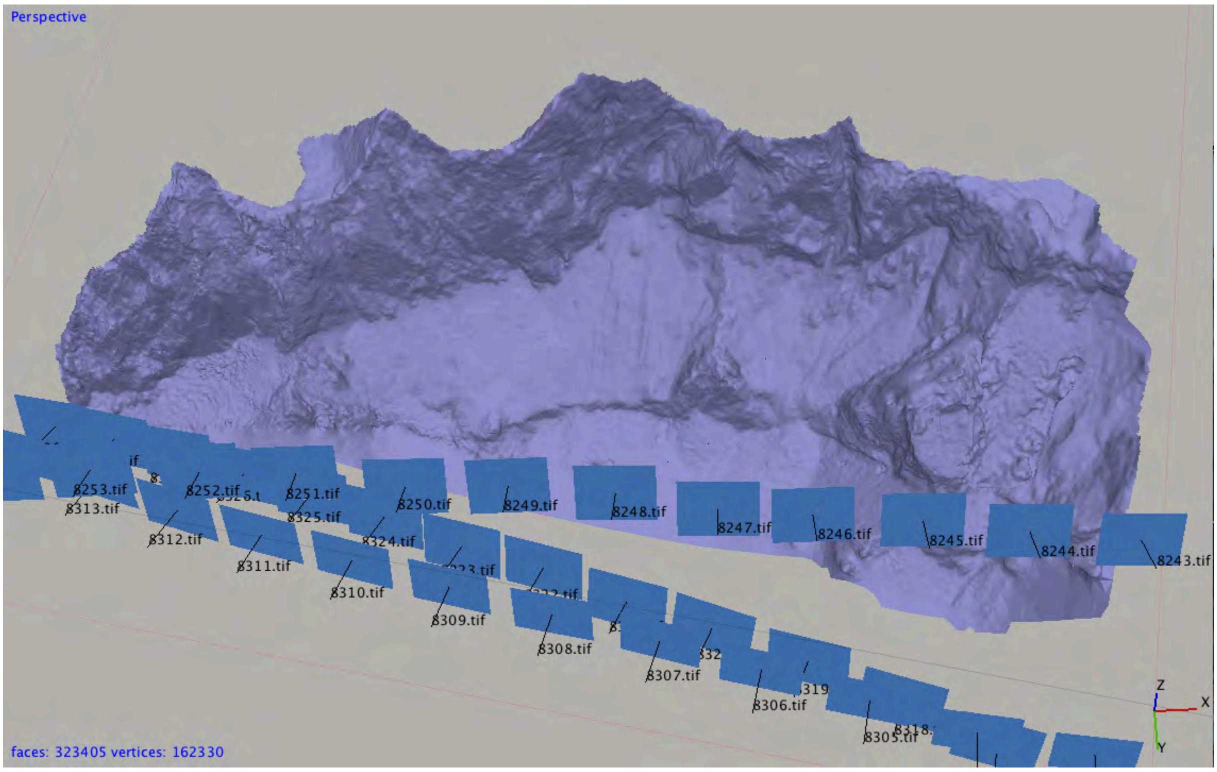


Figure 5.14 Dachstein – HIgh density TIN

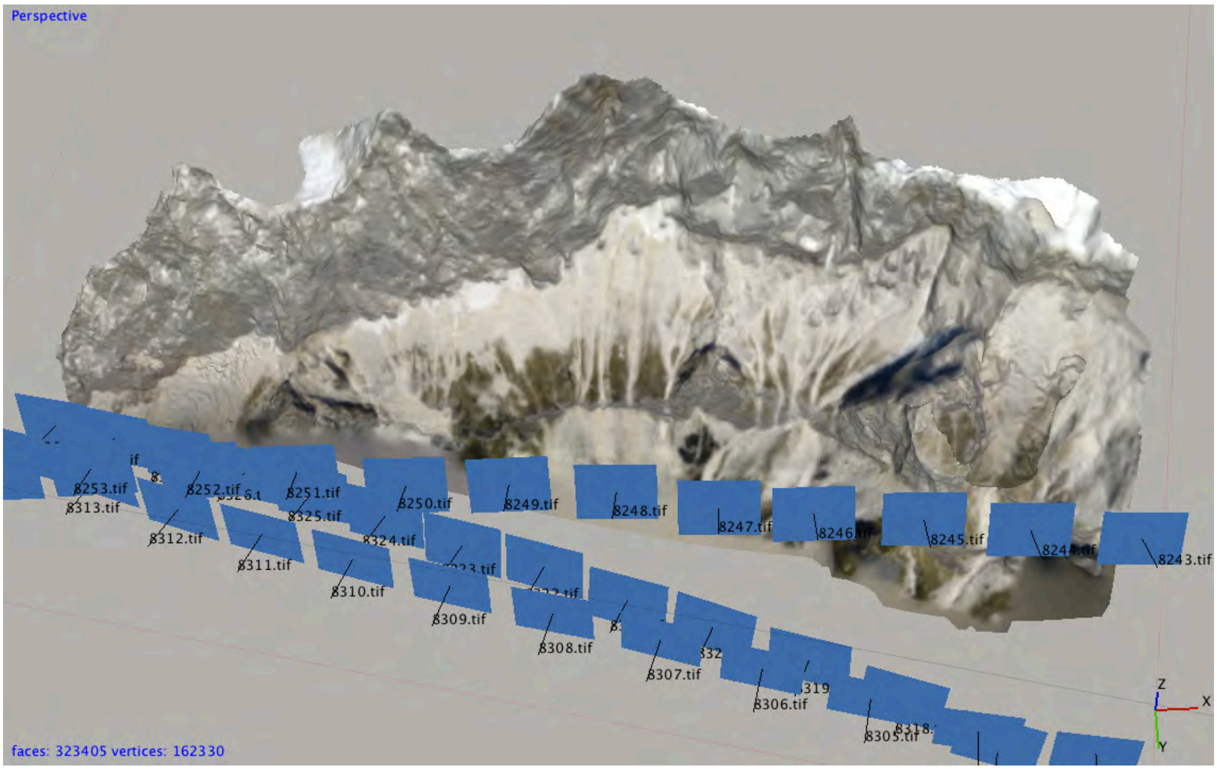


Figure 5.15 Dachstein – Surface model with vertex colors


Figure 5.16 Dachstein – 3D model with photographic texture

Figure 5.17 Dachstein – 3D model from the virtual viewpoint of the LFD

Due to the large computational requirements of this model (Figure 5.17), it could not have been completed without the assistance of Dr. Bernd Hetze of the Center for Information Services and High Performance Computing (Zentrum für Informationsdienste und Hochleistungsrechnen; ZIH) at TU Dresden. Dr. Hetze graciously permitted use of high-powered computers at ZIH that could handle the enormous quantities of data and computations to create a 3D digital model of this size and complexity using SfM.

Dozens of iterations were created over several weeks in the process of determining which functions and parameters were relevant to the final product and which were not. Some versions of the model had as many as 40 million triangles in the mesh and took over 16 hours to generate. This trial-and-error effort, while long and sometimes frustrating, contributed greatly to understanding the capabilities and potential of PhotoScan in particular and SfM in general.

During the iterative process, three difficulties were encountered that are worthy of note. These problems and the corresponding solutions will be discussed in section 5.2.4.

5.2.4 Difficulties

There were no problems in either the alignment or geometry building steps; the three problems encountered were in the texturing step. These are minor and only affected the appearance of the model slightly, but for a large-scale LFD appearance is an important factor, thus solutions were sought.

1. It was noticed that straight lines where the color shifted were sometimes seen across the image (Figure 5.18). These linear artifacts were determined to be the result of inadequate blending at the edges of photographs, even after a blending function had been performed. These most often occurred near the edge of the model, where the matching of photographs was impossible due to there being only one photograph for a particular area. This is unavoidable unless all overlapping photographs are in perfect registration. Fortunately, this is also relatively unimportant because the edge areas are normally cropped from the final model. In some instances, removing a photograph from the texture set alleviated the problem.

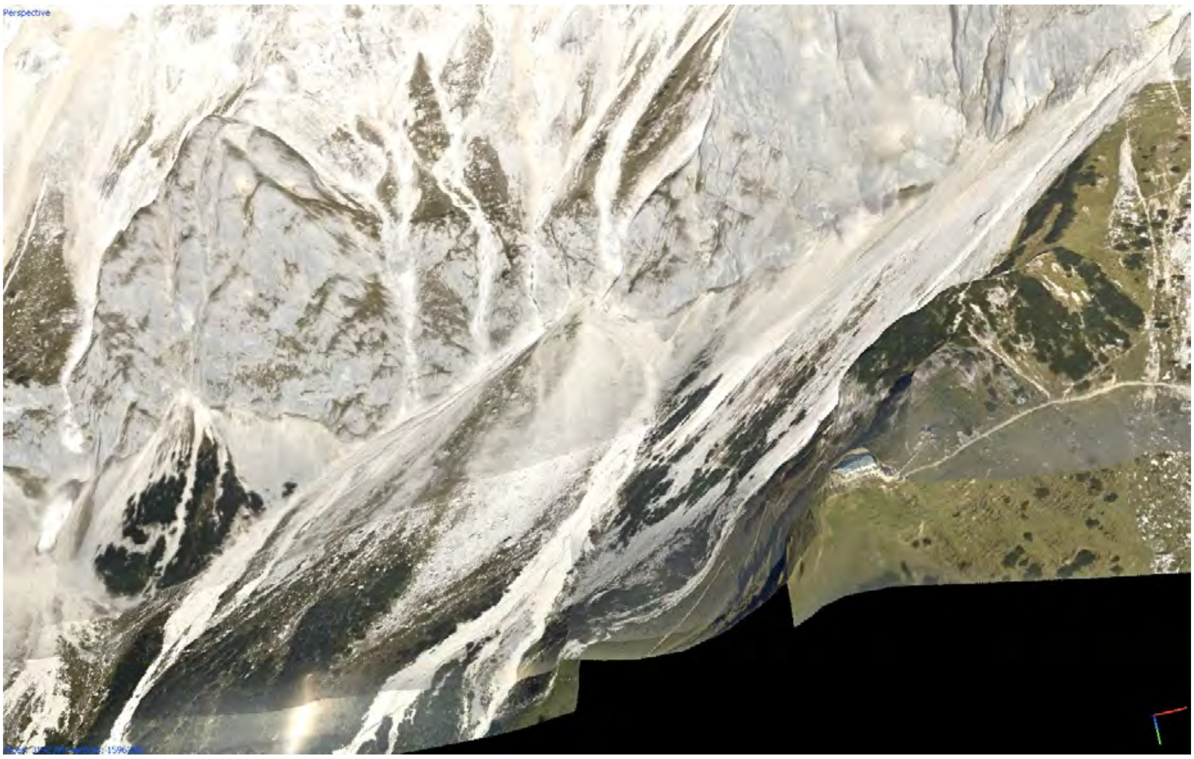


Figure 5.18 Linear artifacts in the texture. Dachstein Südwandhutte is visible in lower right

2. In some areas of the texture, out of focus or ‘double exposure’ areas could be seen. This was the result of too many photos covering the same area. The solution in this instance was also to remove some photos from the texture set until a sharp image was obtained. Ultimately, only 24 of the 39 photos selected were used to build the texture for the model.

3. The most challenging problem was that of the texture resolution. As previously seen in Figure 5.17, the sharpness and clarity of the texture looked good when viewing the model as a whole. But when enlarged to the size required for the planned 6-meter-wide display, the coarseness of the image became apparent (Figure 5.19). The pixels were larger than the width of the lenses in the lenticular foil itself which would destroy the 3D effect when the stereo-mates were interlaced (see Section 5.3.3 below).

Figure 5.19 Low-resolution texture due to *Texture Atlas* settings

Figure 5.20 High-resolution texture from adjusted *Texture Atlas* settings

It was initially thought that the resolution of the source photos was the problem. To save computational effort, the original TIFF images (40MB each)had been converted to smaller JPEG images. The model was regenerated from the TIFF images; the photos were aligned to a higher accuracy, the mesh was generated at a higher triangle count, and the texture was built directly from the TIFFs. Nothing corrected the problem.

Eventually the solution was found in the ***Texture Atlas*** settings under the ***Build Texture*** function. The ***Texture Atlas*** settings determine the final resolution of the model texture, irrespective of the alignment, geometry, or source photographs. Once this had been discovered, appropriate settings height and width were determined and the problem was resolved (Figure 5.20).

5.3 ADDITIONAL STEPS

With the model complete, it was exported as an .fbx file and sent to Prof. Dr. Dirk Stendel at the Nürtingen-Geislingen University of Applied Science (Hochschule für Wirtschaft und Umwelt Nürtingen-Geislingen; HfWU), for stereomate image creation and preparation for printing. The model was visualized with 3D Studio Max software.

5.3.1 3D Visualization

Because of the vertical, almost planar nature of the Dachstein Südwand, it was necessary to increase the apparent depth to insure a strong 3D effect for the LFD. This was done by exaggerating the horizontal dimension of the model in the axis toward the viewer by a factor of 1.5.

Within the 3D modeling environment, lighting can be adjusted. Light from different angles relative to the model affects both the depiction of relief as well as the spatial impression of the image. After viewing the model with lighting from different positions, it was decided that lighting from the front consistently resulted in the best visual effect (Figures 5.21 and 5.22).

Figure 5.21 Dachstein 3D model – illuminated from overhead

Figure 5.22 Dachstein 3D model – illuminated from the front

Prior to the creation of the stereomate images, the model must be placed in a ‘scene’ where the virtual cameras can create images (Gründemann 2004). These scenes are arranged in layers; the parallax shift between the layers resulting from the different camera locations is what gives the spatial impression to viewers of the LFD. This is artificial binocular stereoscopic vision, as described in Section 1.1 and illustrated in Figure 1.2 (p.4).

A title and legend graphic for the display was made with Adobe Photoshop (Figure 5.23). This was placed ‘in front’ of the model in the scene and a ‘sky’ added behind. A mockup showing the final arrangement is shown in Figure 5.24.

Figure 5.23 Title and legend graphic for “Dachstein 3D” LFD

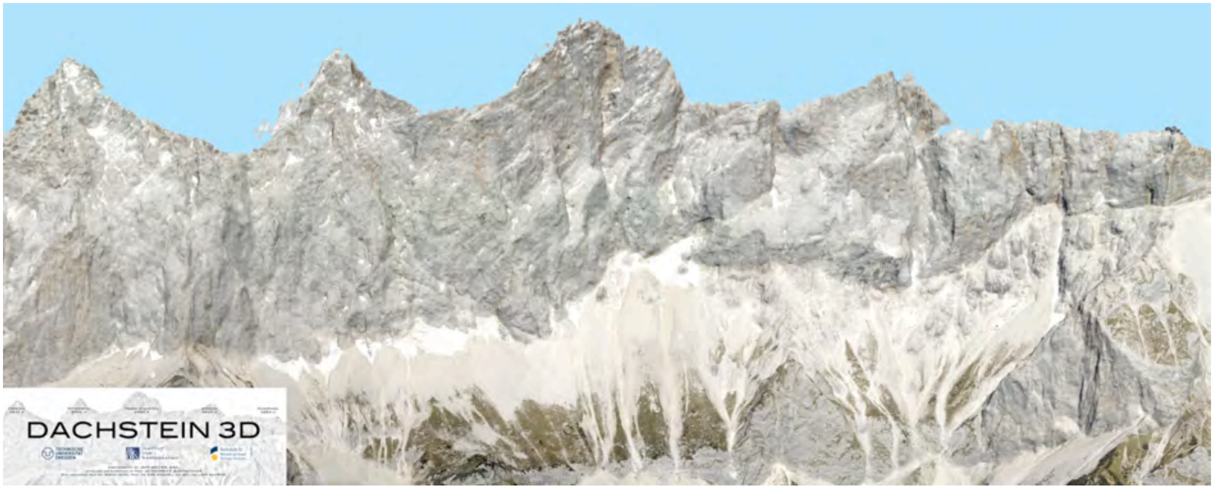


Figure 5.24 Final mockup for “Dachstein 3D” LFD

5.3.2 Stereomate Creation

To create stereomate images of a digital 3D model, multiple overlapping images are taken from different vantage points along a horizontal axis perpendicular to the view toward the subject (Figure 5.25).

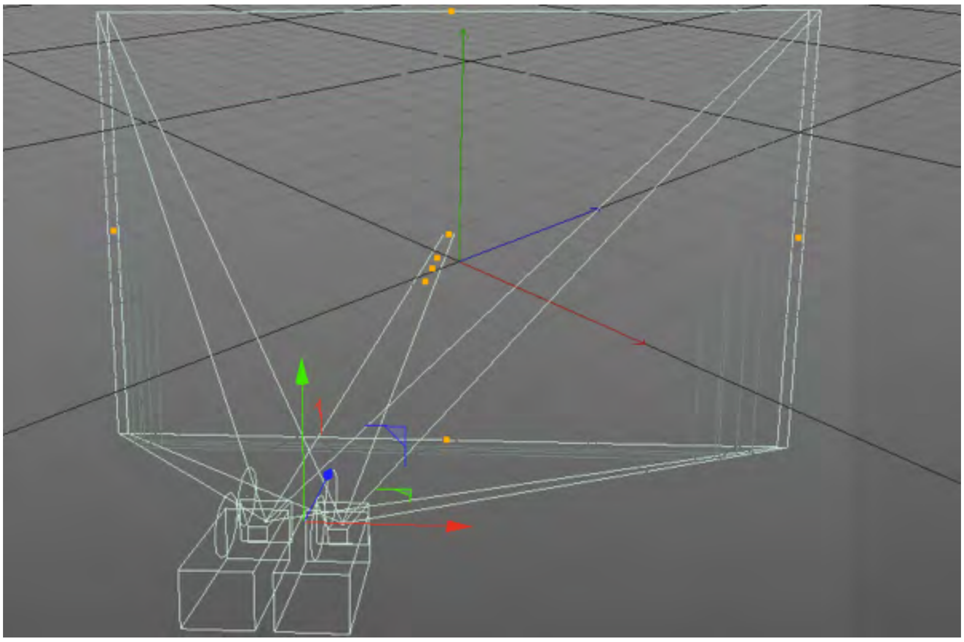


Figure 5.25 Stereomate creation with virtual cameras

Source: Maxon 2012

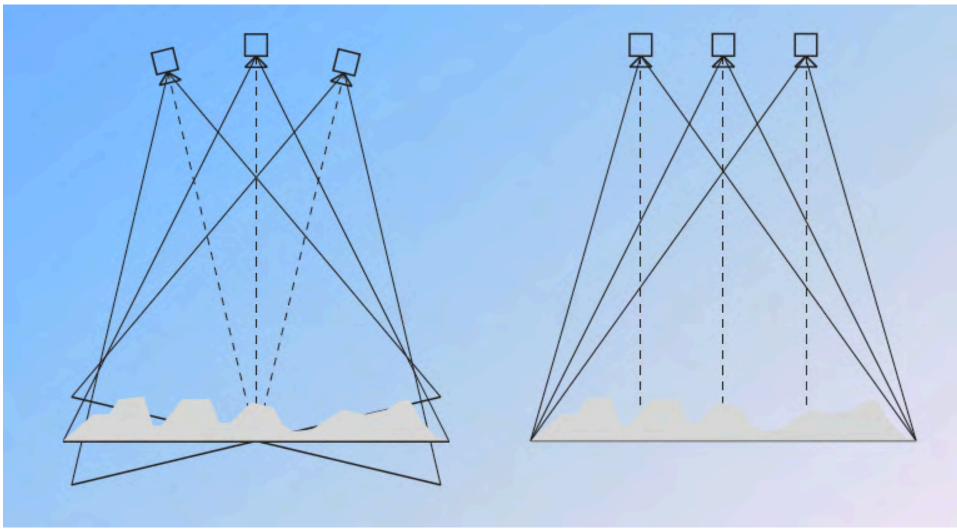


Figure 5.26 Convergent and parallel camera arrangements

Source: Buchroithner et. al. 2006

Cameras can be arranged in two ways: **convergent** or **parallel** (Figure 5.26). In a convergent arrangement, the optical axes intersect at a target point. This has the advantage of ease of set-up, but the disadvantage of distortions near the edges of the scene (Buchroithner 2005). The parallel arrangement overcomes this problem because the views are in a common plane, but at the cost of a more difficult set-up procedure with multiple target points specified.

For this project, cameras were arranged with a parallel orientation and 25 stereomate images were taken. A large number of stereomates reduces 'shifting' or 'jumping' of the image in the LFD that can occur with eye or head motion. This is especially important with large-format LFDs due to the wide angle of view involved.

5.3.3 Interlacing/Printing

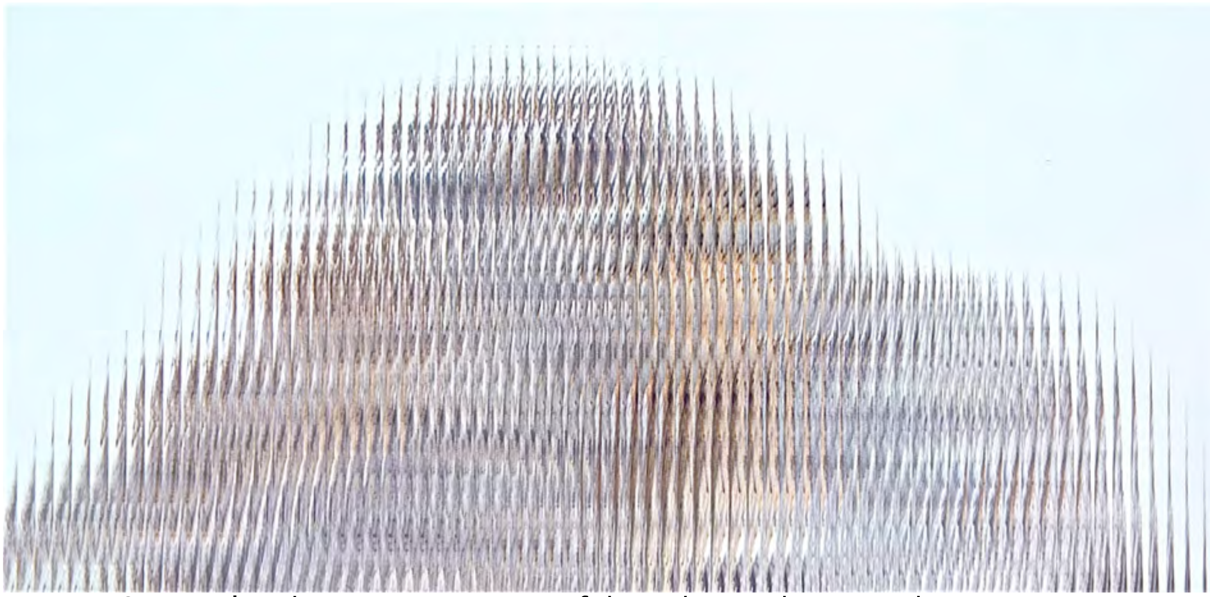


Figure 5.27 Interlaced stereomate images of the Hoher Dachstein peak

Interlacing is the process of digitally cutting the stereomate images into thin strips and arranging them in an alternating pattern (Figure 5.27) so that when placed under the lenticular material and aligned with the lenses, different images are available to each eye of the viewer, creating a 3D spatial impression (see Fig. 1.19, p. 21).

Lenticular foil material is made to different **pitches**, denoting the number of lenses-per-inch (lpi). The strips in the interlaced image must exactly match the pitch of the foil or the 3D spatial impression will not be visible. A sample of the lenticular foil material to be used for the final display was obtained for the purpose of conducting pitch tests. A pitch chart (Figure 5.28), with pitches at 0.1 inch intervals, was printed and the foil was compared against it.

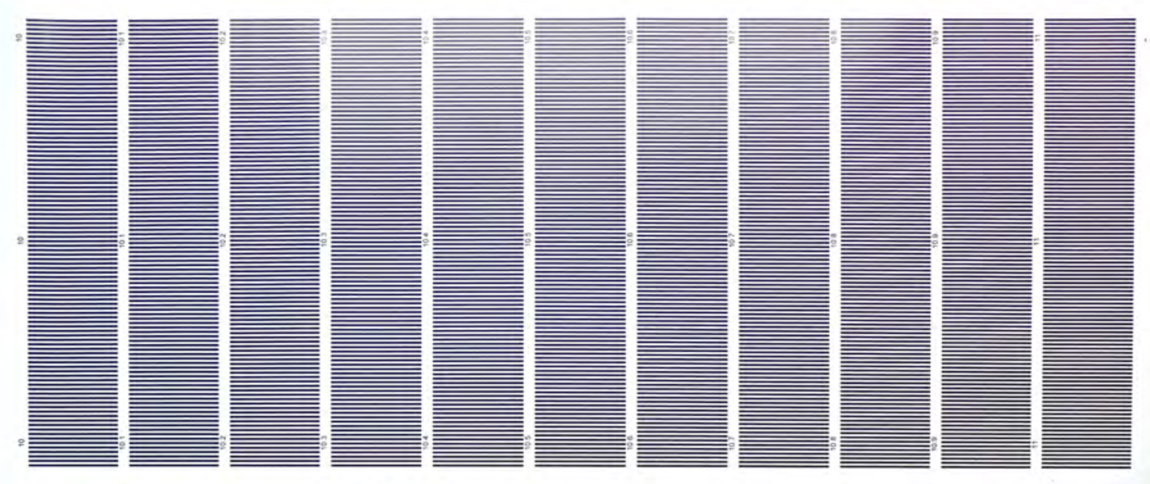


Figure 5.28 Pitch test chart

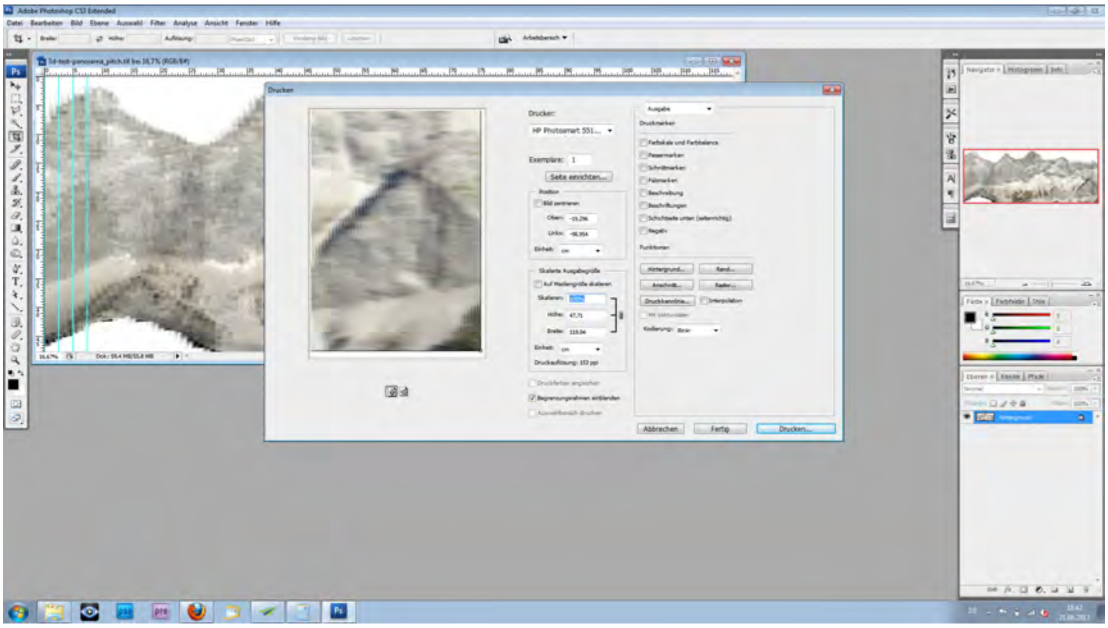


Figure 5.29 Creation of stereomate images

Source: D. Stendel

After determining that the pitch of the foil was in the interval between two of the pitches on the chart, a second chart with pitches at 0.01 inch intervals was printed and the process repeated until the pitch was determined to two decimal places. That pitch factor was applied and the 25 stereomate images were interlaced (Figure 5.29), creating a final image at the designated pitch of 15 lpi, which was sent to the printer. The image was printed on a substrate material which was laminated to the back of the lenticular lens sheet.

5.3.4 Display Construction and Installation

The geometric concept of the display was to have the field of view mimic that as it would seen from the laserscanning position. An observer standing at same vantage point would need an approximately 90˚ field of view to encompass the five major peaks of the Dachstein Massif (Figure 5.30).

Lenticular foil sheets are available in a maximum size of 1.22 x 2.44m., with the lenses running parallel to the long dimension. In order for the 3D spatial impression to be visible, the lenses must be oriented in the vertical direction. Using these criteria, the dimensions of the LFD were set at 6.1 x 2.44m; five full sheets of material oriented vertically. The initial estimation of this can be seen in Figure 5.34 (p. 72).

Because of the limitations of the viewing angle at which the 3D effect can be seen with lenticular foil, it was thought that curving the foil into a 90˚ arc would keep the lenses at the extreme ends of the display within the necessary viewing angle. Calculations determined that the radius required to make a 90˚ arc within 6.1m length is 3.88m.

The supporting structure was designed as five freestanding units with one panel of the display per unit (Figure 5.30). Dimensioned plans were drawn (Figures 5.32 and 5.33) and arrangements were made with LVV-ZEU for the fabrication of the structure.

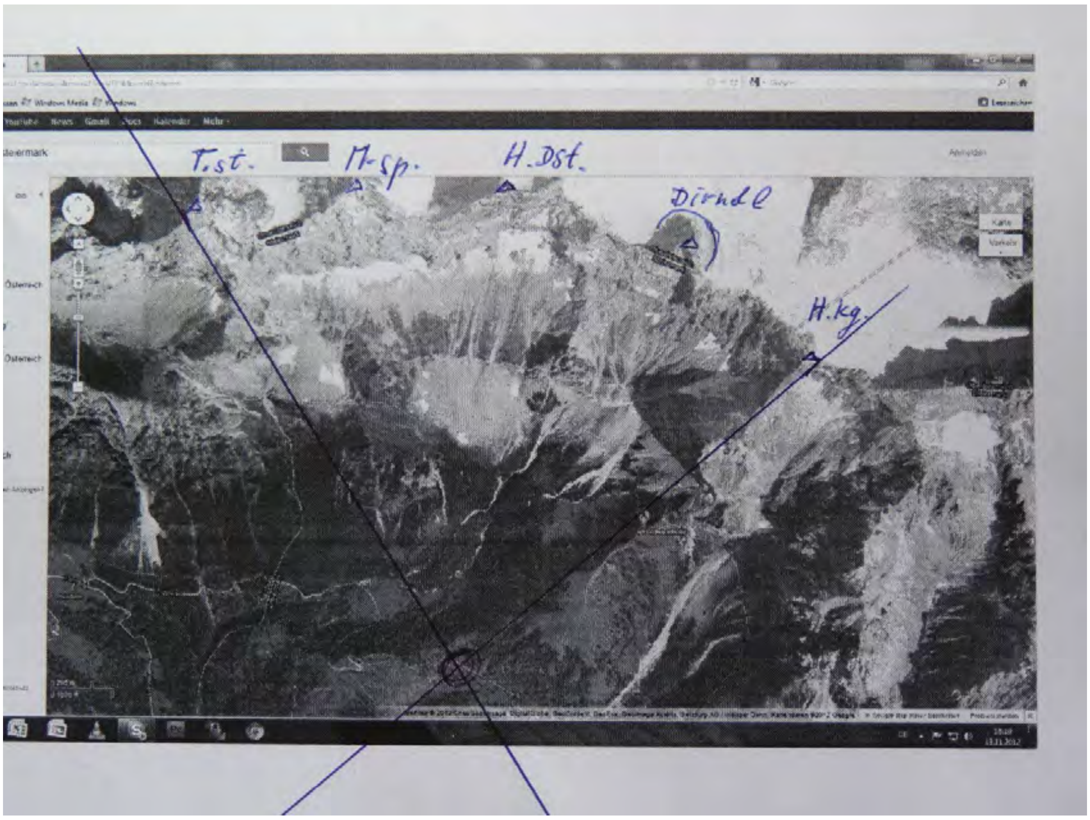


Figure 5.30 LFD structure – Geometric concept

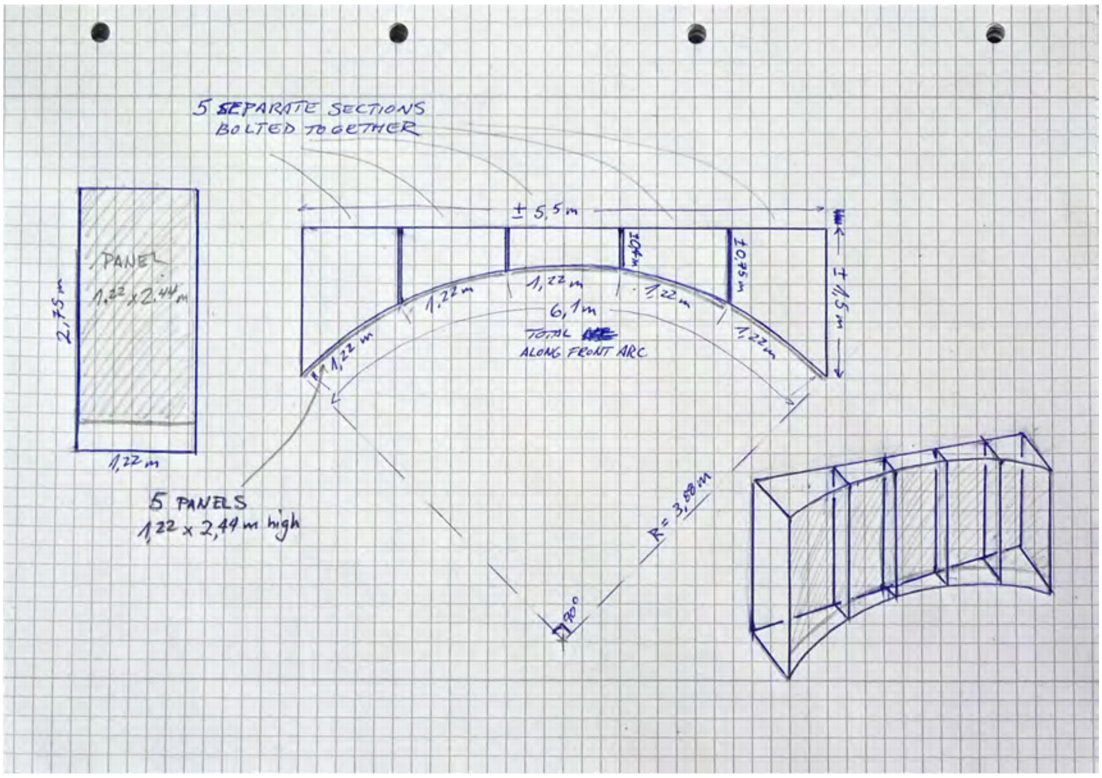


Figure 5.31 LFD structure – Design sketch

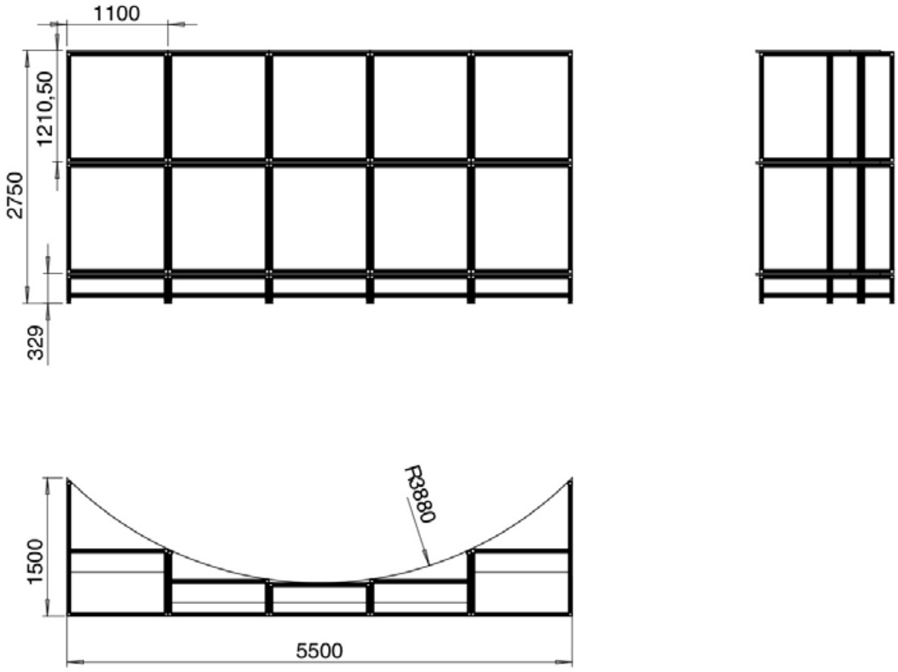


Figure 5.32 LFD structure – Dimensioned drawings

Figure 5.33 LFD structure – Isometric drawing

Source (both figures): L. Gladrow, LVV-ZEU

These decisions were made during the early phases of the project. When the idea of using laserscan data to create the 3D model was dropped and SfM used instead, it was determined that it was not necessary to change the design of the display.

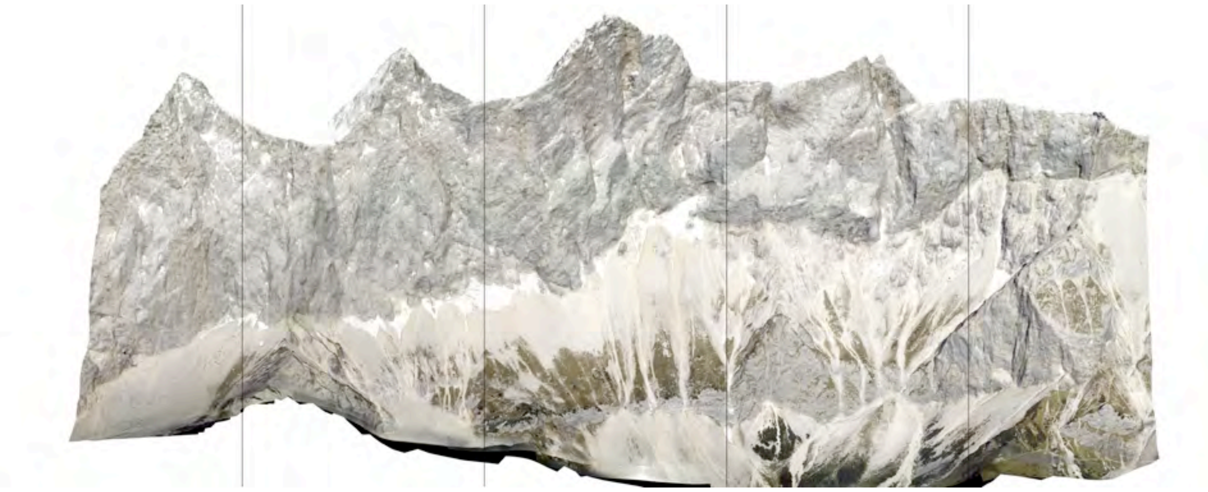


Figure 5.34 Dachstein 3D model showing five divisions for LFD panels

5.3.5 Difficulties

The completed display was to be exhibited at the 26th International Cartographic Conference (ICC2013), held in Dresden in August 2013. The weekend before the opening of the conference, the printed lenticular panels and the completed support structure were delivered to the exhibition site.

As the set up of the display proceeded (Figure 5.35), an unexpected problem arose: the large format lenticular sheets were thicker than anticipated and would not bend to the design radius. Under the time constraints, and lacking materials and tools, an ad hoc solution was reached in that the support structure was rotated 180˚ so that the flat side faced the exhibition. The five panels were then mounted to the structure . The resulting display was planar instead of in an arc, but the results were acceptable under the circumstances (Figure 5.36 and 5.37).


Figure 5.35 LFD structure – Installation

Upon inspecting the installed LFD, two other problems were noticed:

1. The title graphic was the wrong size, which was the result of a simple misreading of the dimension specifications.

2. The entire image was slightly out of focus. The 3D spatial effect was visible, but the resolution and sharpness were not as good as expected. Some questions were voice concerning the quality of the lenticular material itself, as relating both to the optical quality and the curvability.

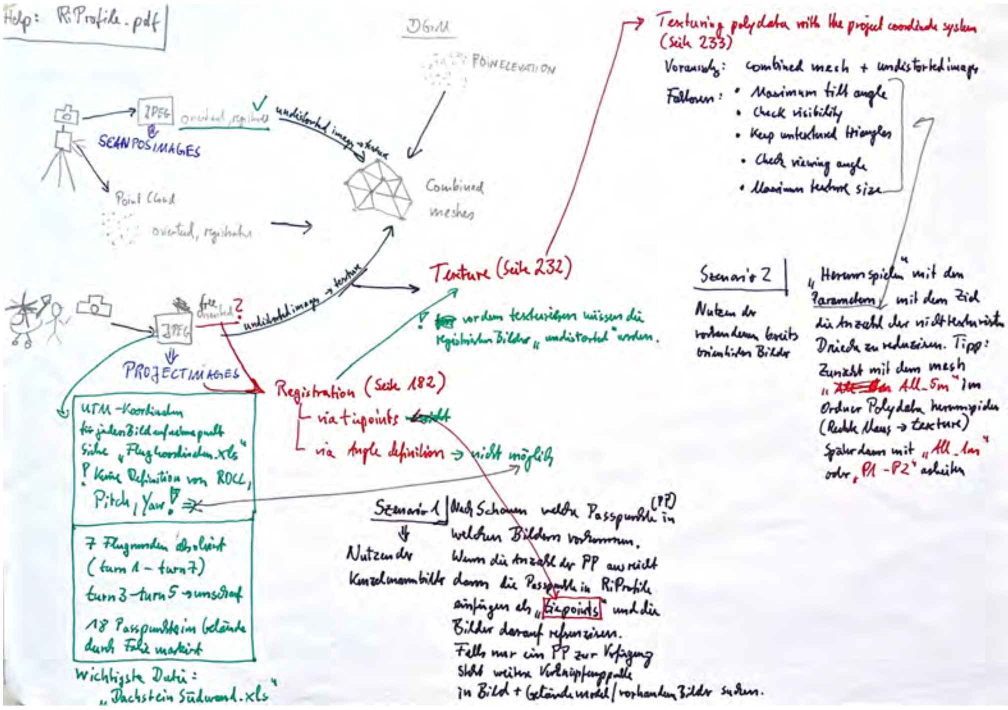
Efforts are being made to understand the causes of these problems and avoid them in future projects. Further research is needed in this area.

Figure 5.36 Completed “Dachstein 3D” LFD

Figure 5.37 “Dachstein 3D” LFD on exhibit at ICC 2013

Despite these problems, the “Dachstein 3D” LFD was successfully exhibited at ICC2013 (Figure 5.38). This display is an innovation for the use of a digital 3D model generated by SfM as the subject of a large format LFD, and is a global first in being the largest cartographic multiviewer autostereoscopic 3D display ever created.

Figure 5.38 Dirk Stendel and Manfred Buchroithner with “Dachstein 3D” LFD at ICC2013



Source: author

6 ANALYSIS

6.1 CNC MOLD

This method holds much promise. Unfortunately, due to the aforementioned production delays, it is impossible to give a complete analysis at this point.

What can be stated is that the generation of the 3D surface model using SfM was simple and produced quality results. When using nadir imagery with this method, the lack of data on the vertical faces is not a drawback, since detail will be added by the cartographer during the sculpting process.

The ease of use of the PhotoScan software combined with the ready and convenient availability of nadir aerial imagery make this an attractive solution to efficiently and economically produce solid terrain models of high-relief regions.

There is much potential with this hybrid method to reduce the time and costs required for the production of STMs and allow these mulitviewer autostereoscopic 3D displays to be more widely used as research tools and as presentations for viewing by the public.

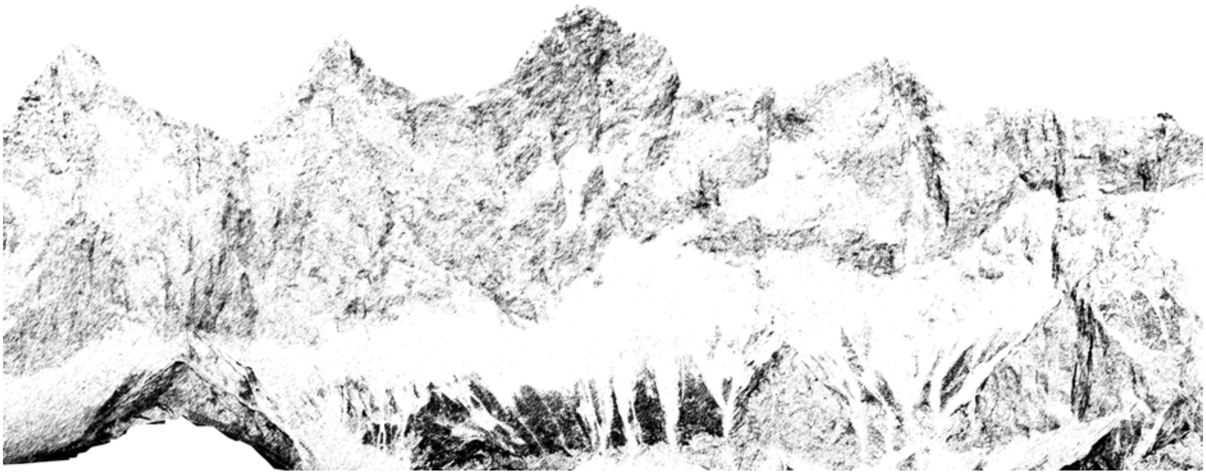
6.2 LENTICULAR FOIL DISPLAY

The visual impact of a large format lenticular foil display is undeniable, and is useful for presentations and lectures to groups of people. A large LFD has multiviewer autostereoscopic 3D capability without the spatial requirement of a similarly-sized STM.

The creation of the digital 3D model using SfM involves no more difficulty than for any other hybrid method, or any pseudo-3D presentation. But creation of a quality digital 3D model is not enough on its own. The subsequent steps in the process, visualization, interlacing, printing, and display, are critical to the final result. Each step must be understood by the cartographer, and quality control must also occur at each step to ensure that the final product is acceptable.

6.3 DACHSTEIN

As a test area, the Dachstein Massif proved to be an excellent choice. The high-relief topography in the forms of slopes, vertical faces, and overhangs, made it possible to test the capabilities of the technologies and methods used in the course of the practical work. The challenge of depicting the terrain in a 3D format required much effort to learn how to get the desired results from the various softwares and tools involved in the process. The problems encountered highlighted the areas where more research is needed.



Source: author

7 CONCLUSION

Initial experiments creating autostereoscopic 3D displays of high relief topography using hybrid methods have demonstrated the potential of combining traditional methods and digital technologies. Solid Terrain Models (STM), a traditional form of autostereoscopic 3D display, can be created with various modern technologies: stereolithography (SL), Fused Deposition Modeling (FDM), or Computer Numerical Control (CNC) milling. Lenticular Foil Displays (LFD) are another form of autostereoscopic 3D display that can be combined with a digital technology to present geospatial data.

Digital 3D models can be used as the starting point for both STMs and LFDs created with hybrid methods. Laserscanning and Structure from Motion (SFM) are two technologies for generating digital 3D models. The speed, ease, and affordability by which highly detailed models can be made with SfM make it an attractive tool for 3D cartographic work.

Large format LFDs have much potential for use in public exhibitions. LFDs are an attractive medium for mulitviewer autostereoscopic 3D presentations. CNC milling holds much promise for rapid and efficient creation of STMs; further research and experiments need to be conducted in this area. Stereolithography and FDM are technologies that also deserve more research.

The two projects conducted in this study prove the usefulness of the hybrid methodologies. Combining a digital 3D model generated with SfM with CNC milling will produce an STM at a substantial savings in time and effort once production delays are overcome. Imaging a textured digital model in a 3D modeling environment and visualizing it with an LFD created a unique cartographic presentation that is the largest of its type to date that has ever been made.

Future research and development of the hybrid methods introduced in this study will expand the role of multiviewer autostereoscopic 3D displays in the field of cartography.

APPENDICES

APPENDIX 1

Solid Landscape Models in the 21st Century - A Balanced Approach

APPENDIX 2

Hybrid Autostereoscopic Methods for Depicting High-Relief Topography

APPENDIX 3

Solid Terrain Model created with CNC milling methods:

Birka, Sweden, circa 800 CE

APPENDIX 1

Solid Landscape Models in the 21st Century - A Balanced Approach

Paper published in The Cartographic Journal Vol. 50 No. 3 International Cartographic Conference - Special Issue August 2013, Dresden. pp. 300-304.

The Cartographic Journal *Vol. 50 No. 3 pp. 300–304 International Cartographic Conference 2013, Dresden – Special Issue August 2013*

OBSERVATIONS

Solid Landscape Models in the Twenty-first Century – A Balanced Approach

Jeff Welter

Dresden University of Technology, Dresden, Germany
Email: ahkbar@hotmail.com

Cartography in general, and building solid landscape models in particular, requires an interdisciplinary set of skills in order to be done well. Traditional handcrafted construction methods provide quality results, but are extremely labour-intensive and therefore costly. Modern methods using digital terrain models (DTMs) and computer numerical control (CNC) milling are fast and accurate, but the finished models are visually less than optimal. Solutions are proposed using DTMs and CNC milling to create landscape models in which the initial shaping is done mechanically and the fine details are carved by hand. This 'balanced approach' to landscape modelling combines the time- and cost-advantages of modern digital technology with the quality of traditional handcrafted techniques resulting in highly accurate landscape models which still retain the artistic 'feel' of the human touch.

Keywords: solid landscape model, DTM, CNC, stereolithography, topographic relief, art

INTRODUCTION

Cartography, as a field of academic research, is somewhat unusual in that it is as much art as science. Many cartographic endeavors require a skill set that goes beyond technical methods and quantitative analyses. This is true for traditional two-dimensional maps and it is even more true when creating a three-dimensional topographic relief – not a 3D computer visualisation or a stereoscopically viewed presentation, but a physical scale model of a portion of the earth's surface. The creation of such a model requires an interdisciplinary approach and training for the cartographer in areas outside the realm of 'traditional' cartography.

Advances in digital technology have opened new means of presentation of cartographic information, especially in the field of 3D. But with these advances, traditional means of presentation should not be overlooked. For viewing in true 3D, solid landscape models still have advantages over newer technologies. Landscape models require no special viewing apparatus such as polarized glasses or 'shutter' glasses. They are instantly understandable to an untrained viewer; no interpretation of contours or shading is required (Buchroithner and Knust, 2013). And they are attractive to viewers. A study conducted between 1992 and 1997 demonstrated that in a setting where both 2D displays and a landscape model are present, approximately 73% of people will spontaneously go to the model within 30 minutes of becoming aware of it (Buchroithner, 2007). This is an important factor for conveying information in this digital age with so many presentation options competing for attention.

But because of the interdisciplinary approach required and the additional time and effort involved to acquire the necessary skills, very few cartographers pursue solid landscape models as a field of research or professional career choice. Toni Mair of Switzerland, one of the handful of professional relief builders in the world, stated that it was only after 15 years' experience that he created his first relief which he considered to be a 'success' (Mair, 2012). While that may seem like an extreme statement and is probably more an expression of Mair's high standards for his work, it does accurately reflect the time and commitment required to become truly proficient.

DEFINITION

A three-fold division

Attempts have been made in the past to locate cartography's 'place' among the sciences, as summarized by Buchroithner and Fernández (2011). It is also commonly expressed that cartography is 'half science, half art'. Most recently, cartography was defined as 'the science, technology, and art of presenting spatial information' (Gartner, 2012). Using this definition as a standard, a well-planned cartographic project should therefore include aspects of all three areas equally.

The theoretical diagram of this definition is shown in Figure 1a, with each area evenly represented and 'in

DOI: 10.1179/1743277413Y.0000000059

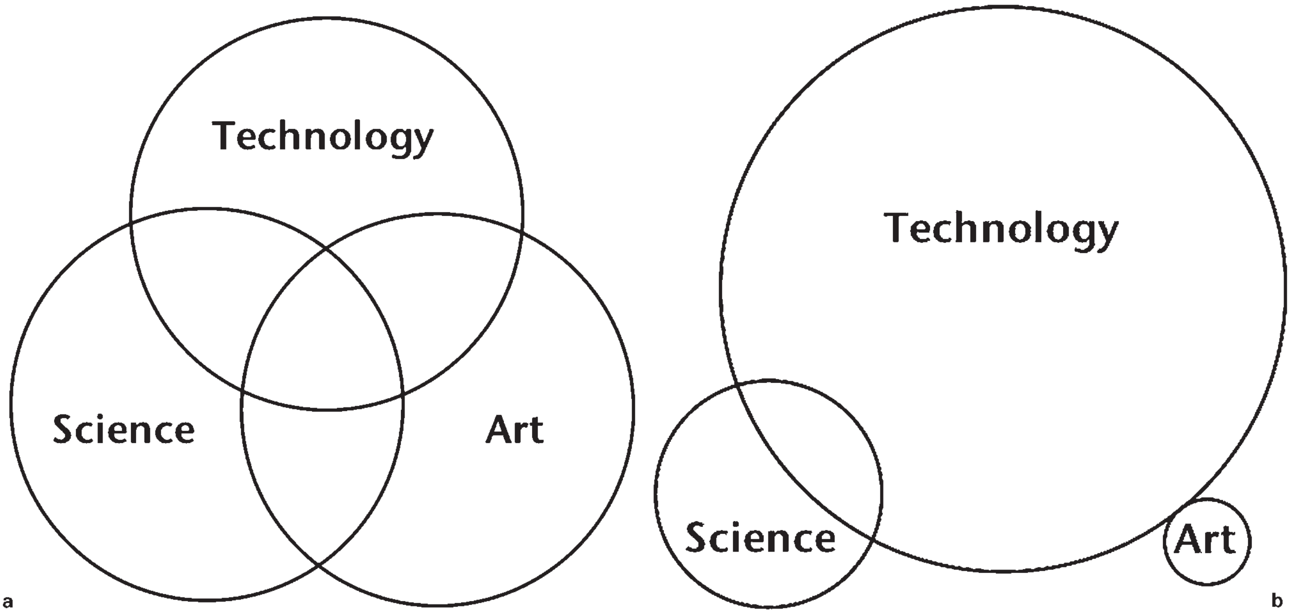


Figure 1. Cartography 'in balance' (a) and 'out of balance' (b)

balance'. The 'ideal map' would be in the centre where all three areas overlap. However, cartography as taught and practiced today is often more like Figure 1b, out of balance with a strong emphasis on technology at the expense of science and art. This is especially a problem at technical universities.

When creating a solid landscape model, a relief builder must overcome this situation and strive to maintain balance in his or her own work. An 'out of balance' skill set will be reflected in the finished model.

Example

This premise can best be illustrated with an example. Two models of the Eiger in Switzerland are shown in Figure 2. The model on the left was created from digital elevation data using computer stereolithography, commonly known as 3D printing. The one on the right is a traditional handmade model by Toni Mair.

The model created with computer stereolithography is technically accurate. The elevations of each point are precise, but it is merely replicating shape. There is no information on the vertical surfaces. There is no knowledge of underlying structure or the processes that influence the form. Most importantly, there is no way of conveying any information beside the form itself to the viewer (the 'snow' was added by the photographer; without it, the relief communicates even less well). By relying too heavily on one set of skills – in this case technology – an inferior result was achieved.

The handmade landscape model has none of those problems. The viewer can see the structure of the rocks and the effects of the erosive processes, and can even infer the time of year from the depiction of snow and runoff.

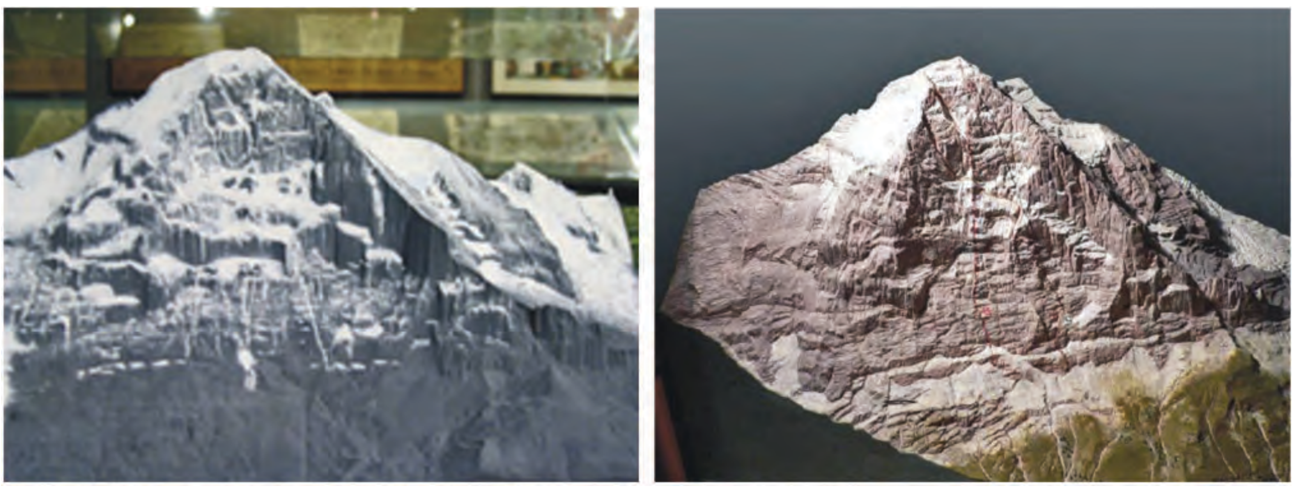


Figure 2. Comparison of computer stereolithographic model and traditional handmade model of the Eiger (photos from Mair, 2012)

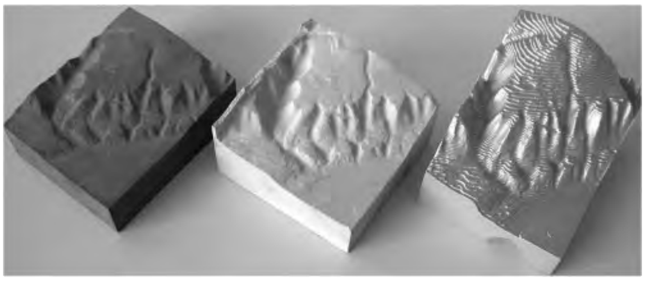


Figure 3. Results of CNC milling tests using DTMs (from Hahmann, 2006)

While it may be less precise in an absolute quantificational sense, it does a much better job of communicating spatial information– by definition, the goal of cartography.

THE PROBLEM OF TIME AND LABOUR

Traditional handmade landscape models have one major drawback – the amount of labour involved to create one. There have been various methods used over the years to create landscape models, but almost all have one process in common: transferring contours from a map to sheets of material, then individually cutting each contour from the material and stacking the resulting pieces in alignment to create a 'core' defining the shape of the terrain, usually referred to as a 'step model'. This core then is either covered with a material (usually plaster) into which the landscape details are carved, or a negative mould is made from the core and a plaster copy is cast. The landscape details are then carved into the plaster copy.

With either method, much labour is required before the cartographer can even begin to model the landscape itself. This results in high time and monetary costs, and therefore fewer models being produced. As Eduard Imhof, founder of the Institute of Cartography at ETH Zurich, lamented in his book *Cartographic Relief Presentation*, 'Authentic terrain models of a quality suitable for presentation…are seldom available'. (2007)

SOLUTION: HYBRID METHODS

With the development in recent years of computer numerical control milling (CNC) and also the availability of digital terrain models (DTMs) derived from digital elevation data, it is now possible to do much of the work of creating a solid landscape model by mechanical means with

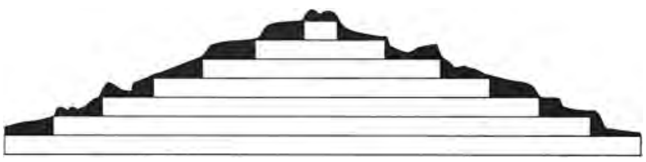


Figure 4. Cross-section of a hypothetical landscape model built using the method described in the section on 'Milling to the profile of an 'eroded' DTM and then cover the resultant core with a layer of material for detail carving' (adapted from Mair and Grieder, 2006)

greater economy in both time and cost. Human skill is used in data preparation before milling (Figure 3), and the final carving and coloring of the landscape – the 'art' of the model.

Following are three basic methods to create a solid landscape model from a DTM using CNC.

Milling directly to the profile defined by the DTM

The most straightforward approach, it involves programming the CNC machine to simply follow the profile of the landscape as defined by the DTM. Tests should be performed to determine the most suitable combination of material to be carved, cutting head and depth of pass to achieve satisfactory results.

This method has been used successfully, for example, to create a relief of the Elbe Valley for a multimedia installation at the Stadtmuseum Dresden (Hahmann *et al.*, 2009). But while the combination of DTMs and CNC works relatively well in low-relief landscapes, for depicting mountainous areas (high relief) it suffers from the same disadvantage as stereo-lithography: lack of detail on vertical or near vertical surfaces.

Milling to the profile of an 'eroded' DTM and then cover the resultant core with a layer of material for detail carving

A method suggested by Toni Mair in the book *Das Landschaftsrelief: Symbiose von Wissenschaft und Kunsthandwerke* is to mill the core of the relief model using CNC and carve the landscape details into the layer of material covering the core for that purpose (Figure 4). This would permit detailing of vertical surfaces. To allow for the thickness of the modelling layer, the profile of the DTM must be 'eroded', a technique borrowed from digital image processing.

This method has the disadvantage that in the process of eroding the DTM, the original profile is lost. While it should be regained with the application of the modelling layer, the accuracy depends entirely on the skill of the builder in maintaining a constant thickness of the applied material. This can be challenging, and is in any case, time-consuming as many thickness measurements must be made during the application process, slowing the overall progress and reducing the economy of time. And if the modelling layer is not applied with due care, the profile of the landscape is altered and the accuracy of the model is compromised.

Milling the 'negative' of the DTM to create a mould from which a 'positive' will be cast of the material to be carved

Some traditional relief builders, instead of making a positive step model to use as a core, make a negative step model to create a mould from which a positive form is cast in plaster. In this instance, instead of cutting 'outside' the contour lines resulting in layers which are stacked to form the basic shape of the model, the cuts in the material are made 'inside' the contour lines creating layers which define the negative space (Figure 5). This method reduces the time and cost of creating a landscape model by eliminating the need to make a separate mould, but requires much visualisation skill on the part of the builder.

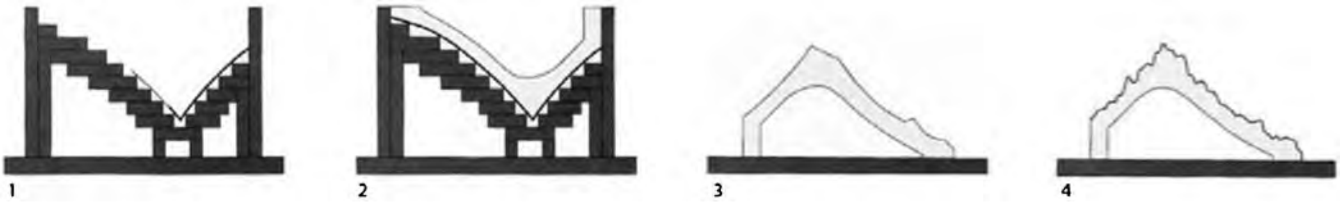


Figure 5. Steps in creating a landscape model from a negative mould (adapted from Räber, 2006, after Imhof)

Figure 6. Author's model of the Großglockner in Austria, constructed using traditional methods (photo by author)

To update this method, instead of milling the positive relief as in the first two examples, the negative of the relief is milled based on the DTM using CNC. The labourious process of cutting and assembling a step model and the process of making a negative mould are combined into one automated function. As stated by Räber and Hurni (2008), 'the relief making process ideally starts with an automatically carved negative form of the future relief model… Hence the time and cost consuming phases of building a step model made of wood could be skipped'.

From first-hand experience constructing solid landscape models using traditional methods (Figure 6), the author estimates that using this method would result in a 40–50% reduction of the time and labour required. Because of the costs associated with CNC milling, cost savings would more likely be approximately 30%. A new project is planned in 2013 to test this method and confirm or disprove the estimates.

CONCLUSION

Utilizing DTMs, CNC milling and traditional handwork in a hybrid methodology to create solid landscape models achieves the desired balance combining the scientific, technological and artistic elements present in a good cartographic product.

To be a successful relief builder, one must be a generalist, not a specialist. The earth itself is a diverse place with many aspects and influences. To be able to recreate a portion of the earth in a solid landscape model, a cartographer must be knowledgeable not only in those diverse aspects and influences, but also in the methods and techniques needed to represent them.

The 'balanced approach' to solid landscape modelling combines the time- and cost-advantages of modern digital technology with the quality of traditional handcrafted techniques resulting in highly accurate models which still retain the artistic 'feel' of the human touch. This will ensure that the traditional handmade landscape model will have a future in the digital world of the twenty-first century.

BIOGRAPHICAL NOTES

After earning a Bachelor's degree in Geography, Jeff Welter worked as a surveyor's assistant, freelance cartographer and sculptural artist. He is currently completing his Master's thesis as part of the International Cartography Master program offered jointly by the Technical University of Munich, TU Vienna and TU Dresden, after which he plans on continuing his studies towards a PhD. His main academic interests are 3D cartography and topographic relief presentation, as well as archaeology and history. Jeff was the winner of the 2012 ICA Video Contest with his video 'Troy's Wish'. When not creating maps of mountains, he enjoys hiking, snowboarding and travelling the world.

REFERENCES

Buchroithner, M. (2007). 'Echtdreidimensionalität in der Kartographie: Gestern, heute, und morgen', **Kartographische Nachrichten**, 57, pp. 240–248.

Buchroithner, M. and Fernández, P. (2011). 'Cartography in the context of sciences: theoretical and technological considerations', **The Cartographic Journal**, 48, pp. 4–10.

Buchroithner, M. and Knust, C. (2013). 'True-3D in cartography: current hard- and softcopy developments', in **Geospatial Visualisation**, Lecture Notes in Geoinformation and Cartography, ed. by Moore, A. and Drecki, I., pp. 42–64, Springer-Verlag, Berlin.

Gartner, G. (2012). Personal communication.

Hahmann, T. (2006). Bearbeitung digitaler Geodaten für ein Reliefmodell des Dresdener Elbtales sowie Untersuchungen zu Umgebungsvariablen für die Projektion eines Filmes auf das Relief. Unpublished seminar paper. Institute for Cartography, Dresden University of Technology. Dresden, Germany.

Hahmann, T., Eisfeld, C. and Buchroithner, M. (2009). 'Cartographic representation of Dresden's historical development by projecting a movie onto a solid terrain model', in **True-3D in Cartography: Autostereoscopic and Solid Visualisation of Geodata**, Lecture Notes in Geoinformation and Cartography, ed. by Buchroithner, M., pp. 281–296, Springer-Verlag, Berlin.

Imhof, E. (2007). **Cartographic Relief Presentation** (reprint), ESRI Press, Redlands, CA.

Mair, T. (2012). 'The landscape relief model – an anachronism or a still useful object for contemplating the landscape?', in **True-3D in Cartography: Autostereoscopic and Solid Visualisation of Geodata**, Lecture Notes in Geoinformation and Cartography, ed. by Buchroithner, M., pp. 415–434, Springer-Verlag, Berlin.

Mair, T. and Grieder, S. (2006). **Das Landschaftsrelief: Symbiose von Wissenschaft und Kunsthandwerk mit Schweizer Reliefkatalog**, Hier + Jetzt Verlag, Baden.

Raber, S. and Hurni, L. (2008). 'An ambitious relief model project: a combination of a handmade, a computer-generated and a profiled relief model', in **Proceedings of the 6th ICA Mountain Cartography Workshop**, ed. by Hurni, L. and Kriz, K., pp 185–193, ETH Zurich Institute of Cartography, Zurich.

Räber, S. (2006). 'Handmade relief models', in **Proceedings of the 5th ICA Mountain Cartography Workshop**, ed. by Petrovič, D., pp. 222–227, Association of Surveyors of Slovenia and University of Ljubljana, Ljubljana.

APPENDIX 2

Hybrid Autostereoscopic Methods for Depicting High-Relief Topography

Poster selected for and presented at the International Cartography Conference held in Dresden, Germany, August 2013.

TECHNISCHE UNIVERSITÄT MÜNCHEN

TECHNISCHE UNIVERSITÄT DRESDEN

TECHNISCHE UNIVERSITÄT WIEN

Hybrid Autostereoscopic 3D Methods for Depicting High-Relief Topography Case study: Dachstein, Austria

Jeff Welter

Student, MSc. in Cartography

(TU Munich, TU Vienna, TU Dresden)

2013

Master's Thesis

Supervisor: Prof. Dr. Manfred F. Buchrothner

Institute for Cartography, Technical University of Dresden

Introduction

Solid terrain models are the traditional form of autostereoscopic (viewable without additional viewing aids) 3D depiction of topography. Digital 3D models increase accuracy and save labor, but are not autostereoscopic. Combining the latest 3D technologies with traditional cartographic methods can give improved terrain models at a lower cost, especially for models depicting areas of high topographic relief. For a test of this, the Dachstein Massif in Austria was chosen.

Structure from Motion (SfM)

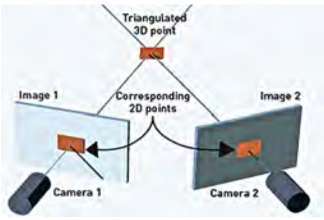


Figure 1: The basic principle of Structure from Motion. (Image: www.visionrt.com)

The technique of reconstructing 3D from 2D images by matching points and triangulation is called Structure from Motion (SfM). Originating in Photogrammetry and Computer Vision, SfM enables the creation of 3D digital models without the need for laserscanning. The imagery used can be conventional aerial photos, but can also be obliquely-acquired photos taken with handheld cameras. Photos do not need to be georeferenced, although this is possible if desired.

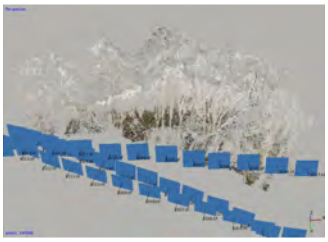


Figure 2: Point cloud of vertices matched between images. Blue rectangles denote photo locations.

Solid Terrain Models

Solid terrain models have a long history and a special place in Cartography as being the original autostereoscopic displays. Traditional construction methods provide excellent results, but are time consuming and labor intensive, resulting in high costs of production. Modern production methods using DEM files and stereolithography (3D printing) give good results in low relief landscapes, but the results in high mountain topography are less than satisfactory due to the lack of information on vertical or near-vertical faces. This is because the elevation data has been captured from a nadir position. Since SfM can use oblique photographs, this problem is overcome. Digital models made with SfM from oblique photos contain more data about the shape of the landscape than just elevation spot heights, resulting in more accurate representation of the landform. These models can then be used to generate solid terrain models or other autostereoscopic displays using digital technologies such as CNC milling, stereolithography, or lenticular Foil.

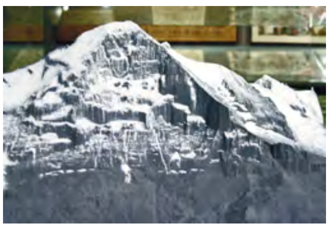


Figure 3: Lack of detail on vertical surfaces when 3D printed model is created from DEM data. (Photo: T. Mair)

CNC Milling

Figure 4: Digital terrain model created with SfM using nadir imagery.

Computer Numerical Control (CNC) milling has been used in the past to create solid terrain models by milling to the contours of the landscape. But by inverting the digital surface model and converting to CNC command codes, this technique can be also be used to mill a negative mold from which positive copies can be cast in a carveable material. These copies are then finished by hand-carving and coloring to match photographs of the actual terrain, thereby combining traditional and modern methods to produce a lower cost model that retains the quality of artisanal work.

Figure 5: Inverted digital terrain model for CNC milling of a mold for casting a solid terrain model.

Stereolithography (3D Printing)

The process for creating a model using stereolithography is more involved. In this example, the model is designed for printing using the Fused Deposition Modeling (FDM) process, in which material is fed to the print head in a liquid state and built up in layers. The same digital surface model is used as a starting point, but because it has no thickness, it must be extruded into a "solid" using 3D modeling software. This solid form must have the property of being "watertight", i.e. having no holes in the triangular mesh. This model is then converted into a stack of "slices", layers for printing.

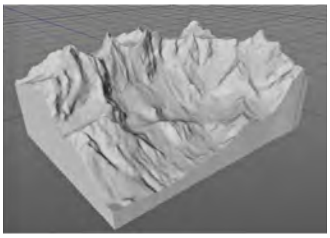


Figure 6: Digital model for Stereolithography (3D Printing) using Fused Deposition Modeling (FDM).

Figure 7: Textured 3D model of Dachstein Südwand for Lenticular Foil display.

Lenticular Foil Display

Figure 8: Close-up view of the edge of a sheet of lenticular foil (Photo: Wikimedia Commons)

For lenticular foil display, an entirely different approach is used. A digital model is created as in the other methods, but since appearance is important as well as shape, 'texture' must be applied i.e the model must be 'draped' with the photographs. The quality of the texture is determined by the parameters of the 'texture map', not the resolution of the original photos. Once the digital model is created, it is opened in 3D modeling software and multiple overlapping images of the model are taken using the software's virtual camera. Lighting, view angle, aspect, and position are all controllable to a degree not usually possible in the 'real' world. Lenticular foil consists of multiple linear lenses which direct different parts of the image to each eye. By interlacing thin strips of each image and accurately locating them behind the lenses, stereovision and perceived depth are achieved for the viewer.

Figure 9: Interlaced stereomate images.

Figure 10: Resolution is determined by texture map parameters rather than by the original image.

Conclusion

Initial experiments creating autostereoscopic models of high relief topography with these hybrid techniques have shown the potential of combining traditional methods and digital technologies. Future development will expand the role of 3D in the field of cartography. The Dachstein has proven to be a valuable test case.

References

Buchroithner, M. and Knust, C. (2013). 'True-3D in cartography: current hard- and softcopy developments', in **Geospatial Visualisation**, Lecture Notes in Geoinformation and Cartography, ed. by Moore, A. and Drecki, I., pp. 42-64, Springer-Verlag, Berlin.

Mair, T. (2012). 'The landscape relief model - an anachronism or a still useful object for contemplating the landscape?', in **True-3D in Cartography: Autostereoscopic and Solid Visualisation of Geodata**, Lecture Notes in Geoinformation and Cartography, ed. by Buchroithner, M., pp. 415-434, Springer-Verlag, Berlin.

Räber, S. and Hurni, L. (2008). 'An ambitious relief model project: a combination of a handmade, a computer-generated and a profiled relief model', in **Proceedings of the 6th ICA Mountain Cartography Workshop**, ed. by Hurni, L. and Kriz, K., pp. 185-193, ETH Zurich Institute of Cartography, Zurich.

APPENDIX 3

Solid Terrain Model created with CNC milling methods:

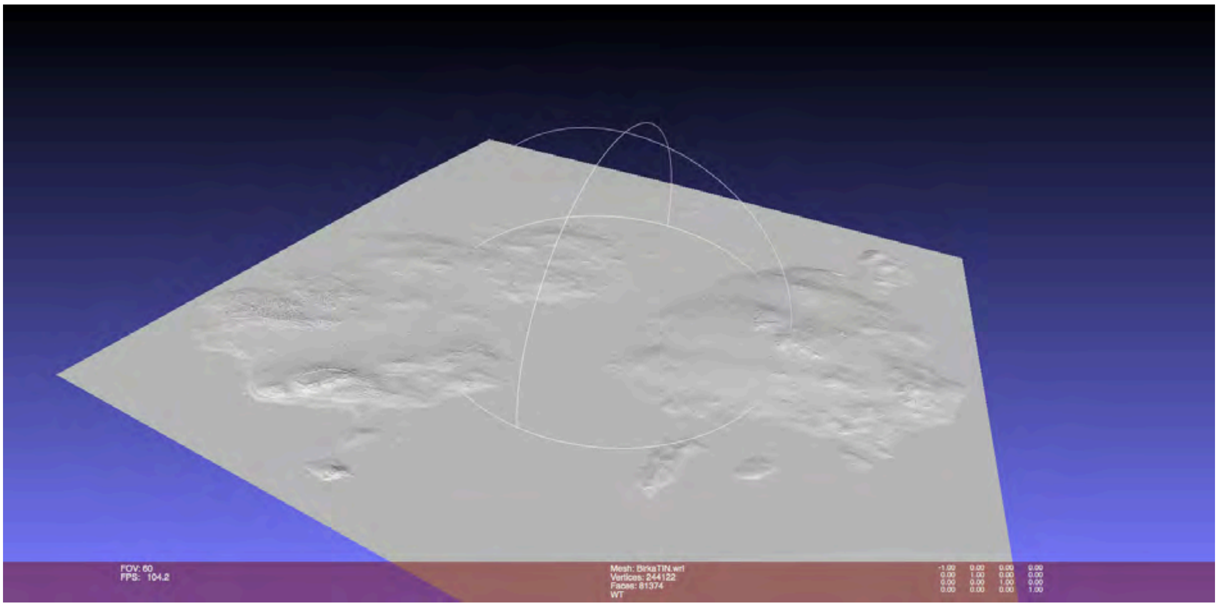
Birka, Sweden, circa 800 CE

Project done in conjunction with the Ludwig Boltzmann Institute of Archaeological Prospection, Vienna, Austria.

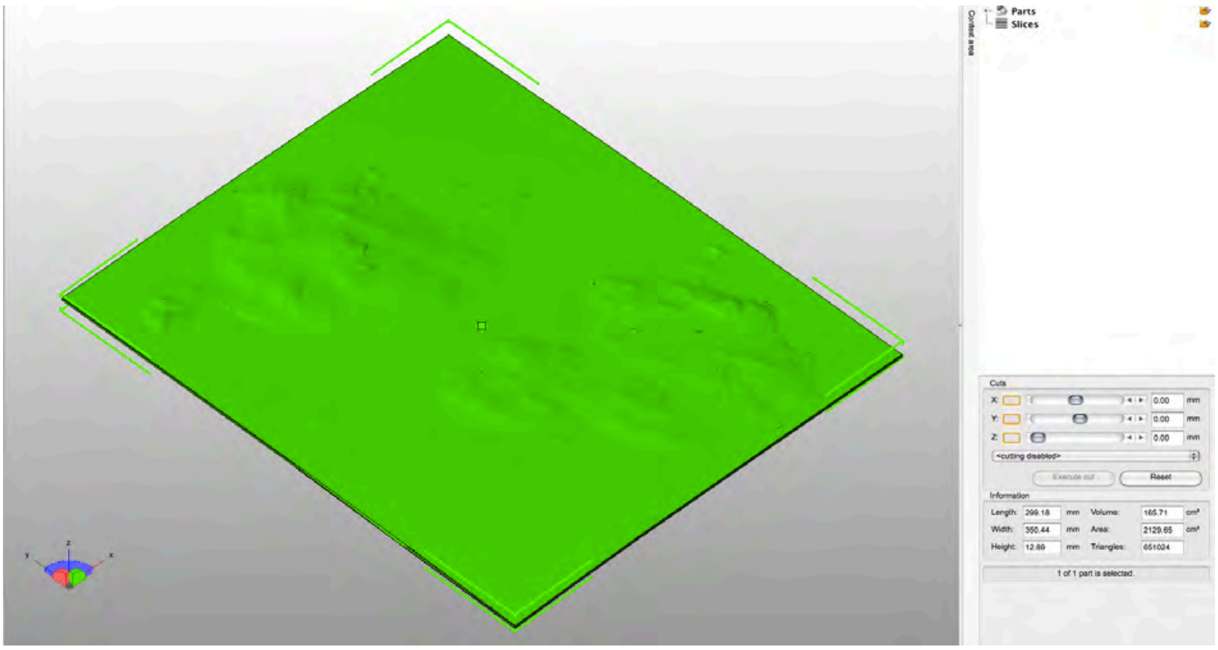
The relief depicts the island of Birka, location of an important Viking settlement (now an archaeological site), as it was in the year 800 CE, when water levels were approximately 5 meters higher than today, due to the rebounding of the earth's crust after the last Ice Age. The lighter blue areas denote the current extent of the island. Scale of the relief is 1:12000.

I would like to express thanks to Dr. Wolfgang Neubauer, Dr. Immo Trinks, and Dr. Geert Verhoeven of LBI ArchPro for their assistance with this project.


A3.1 Artist's concept - Initial visualization of DTM in Terrain Bender



A3.2 Visualization of DTM in Meshlab



A3.3 Conversion to .stl file in NetFabb

A3.4 Topographic relief model after the CNC milling process

A3.5 Completed solid terrain model

A3.6 Solid terrain model - Birka, Sweden, ca. 800 CE

BIBLIOGRAPHY

Agisoft LLC. (2013a) Agisoft PhotoScan User Manual Standard Edition, Version 0.9.1. Available online at www.agisoft.ru/products/photoscan/standard/. Last accessed September 2013.

Agisoft LLC. (2013b) Tutorial (Intermediate level): 3D Model Reconstruction with Agisoft PhotoScan 0.8.5. Available online at www.agisoft.ru/tutorials/photoscan/02/. Last accessed September 2013.

Birsak, L. (2011) Kozenn–Atlas: Eine kurze Geschichte zum 150. Geburtstag eines Meilensteins der österreichischen Schulkartographie. Ed. Hölzel Gesellschaft, Vienna.

Buchroithner, M.F., Wälder, O., Habermann, K. and König, B. (2003) Generating a True-3D image map of high relief terrain using lenticular foil. Proceedings of the 21st International Cartographic Conference, Durban, South Africa, pp. 1323-1328.

Buchroithner, M. (2005) True-3D Visualisation of Remote Sensing Data of High-Alpine Terrain. In: Oluić, M. (ed.) New Strategies for European Remote Sensing. Millpress, Rotterdam, pp. 129-136.

Buchroithner, M., Habermann, K. and Gründermann, T. (2005) Modeling of Three-Dimensional Geodata Sets for True-3D Lenticular Foil Displays. Photogrammetrie–Fernerkundung–Geoinformation 2005/1:47-56.

Buchroithner, M. Walther, S. and Habermann, K. (2006) Development of New Types of Glacier Dynamic Maps. Presentation at the 5th Mountain Cartography Workshop of the Commission on Mountain Cartography of the ICA. Bohinj, Slovenia, 29 March - 1 April 2006. Available online at www.mountaincartography.org/publications/papers/papers_bohinj_06/index.php. Last accessed September 2013.

Buchroithner, M. (2007) Echtdreidimensionalität in der Kartographie: Gestern, heute, und morgen. Kartographische Nachrichten 57/5:240-248.

Buchroithner, M.F. (2008) We Make You See the World 3D: Lenticular Foil Geo-Displays. In: Proceedings of the 13th International Conference on Geometry and Graphics (ICGG), August 4-8, 2008, Dresden (Germany) CD-ROM

Buchroithner, M., Ehlert, G., Hetze, B., Kohlschmidt, H., and Prechtel, N. (2013) Satellite-Based Technologies in Use for Extreme Nocturnal Mountain Rescue Operations: a Synergetic Approach Applying Geophysical Principles. Pure and Applied Geophysics. July 09, 2013, pp. 1-11.

Buchroithner, M. and Fernández, P. (2011) Cartography in the Context of Sciences: Theoretical and Technological Considerations. Cartographic Journal 48:4-10.

Buchroithner, M. and Knust, C. (2013a) True-3D in Cartography–Current Hard- and Softcopy Developments. In: A. Moore and I. Drecki (eds.), Geospatial Visualisation, Lecture Notes in Geoinformation and Cartography, Springer-Verlag, Berlin Heidelberg, pp 41-65.

Buchroithner, M. and Knust, C. (2013b) The Third Dimension in Cartography: Recent and Future Developments. Kartographische Nachrichten 63/Sonderheft (June 2013).

Caminada, P. (2003) Pionere der Alpentopographie: Die Geschichte der Schweizer Kartenkunst. AS Verlag & Buchkonzept, Zürich.

Deutscher Alpenverein (2006) Alpenvereinskarte Glocknergruppe1:25000, Nr. 40.

Dodgson, N.A. (2005). Autostereoscopic 3D Displays. IEEE Computer 38/8:31–36.

Doneus, M. Verhoeven, G. Fera, M. Briese, C. Kucera, M. and Neubauer, W. (2011) From deposit to point cloud – a study of low-cost computer vision approaches for the straightforward documentation of archaeological excavations. Geoinformatics 6. XXIIIrd International CIPA Symposium. Faculty of Civil Engineering. Czech Technical University in Prague. Pp. 81-88.

Ehlert, H. (2013) Untersuchungen zur Genauigkeit von Structure-from-Motion Tools. Unpublished Bachelor's thesis, Technical University of Dresden.

eFunda (2013) CNC Milling. eFunda (website) www.efunda.com/processes/machining/mill_cnc.cfm. Last accessed September 2013.

Fergus, R. (2013) Lecture 6: Multi-view Stereo & Structure from Motion. Course slides for Computer Vision CSCI-UA.0480.002 at New York University. Published online at www.cs.nyu.edu/~fergus/teaching/vision/. Last accessed April 2013.

Fricker, P., Girot, C., Kapellos, A., Melsom, J. (2011): Landscape Architecture Design Simulation: Using CNC Tools as Hands-On Tools. In: Buhmann/Pietsch/Kretzler (Eds.): Peer-reviewed Proceedings Digital Landscape Architecture 2011, Anhalt University of Applied Sciences. Wichmann Verlag, Offenbach.

Gartner, G. (2012) Personal communication.

Gede, M. and Mészáros, J. (2013) Digital Archiving and On-line Publishing of Old Relief Models. The Cartographic Journal 50/3:293-299.

Gladrow, L. (2013) Personal communication. Email received 16.08.2013.

Gründemann, T. (2004) Grundlagenuntersuchungen zur kartographischen Echt-3D-Visualisierung mittels des 3D-Lentikularverfahrens. Studentarbeit, TU Dresden, 45p.

Habermann K (2004) Conception for True-3D Maps. Presentation at the XIII. Cartographic School 2004 of University Breslau: Co zwie si koncepcj mapy? - What is called the Map Conception?. pp. 76–88.

Hahmann, T. (2006) Bearbeitung digitaler Geodaten für ein Reliefmodell des Dresdener Elbtales sowie Untersuchungen zu Umgebungsvariablen für die Projektion eines Filmes auf das Relief. Unpublished seminar paper, Institute for Cartography, Technical University of Dresden.

Hahmann, T.; Eisfeld, C.; and Buchroithner, M. (2009) Cartographic Representation of Dresden's Historical Development by Projecting a Movie onto a Solid Terrain Model. In: M. Buchroithner (ed.), True-3D in Cartography: Autostereoscopic and Solid Visualisation of Geodata, Lecture Notes in Geoinformation and Cartography, Springer-Verlag Berlin Heidelberg, pp 281-295.

Hurni, L. (2008) Cartographic Mountain Relief Presentation 150 years of Tradition and Progress at ETH Zurich. In: Hurni, L. and Kriz, K. (eds.) Mountain Mapping and Visualisation: Proceedings of the 6th ICA Mountain Cartography Workshop, Lenk, Switzerland, 11-15 February 2008, pp. 85-91.

Imhof, E. (2007) Cartographic Relief Presentation (reprint). ESRI press, Redlands.

Institute of Cartography and Geoinformation, ETH Zurich (2012) Relief Artists. Terrain Models (website) www.terrainmodels.com/artists.html. Last accessed September 2013.

Jebara, T., Azarbayejani, A. and Pentland, A. (1999) 3D Structure from 2D Motion. MIT Media Laboratory, Perceptual Computing Technical Report #523. In: IEEE Signal Processing Magazine 16/3: (no page numbers).

Kjellman, E. (2012) From 2D to 3D – A photogrammetric revolution in archaeology? Unpublished Master's thesis, University of Tromsø. Available online at munin.uit.no/handle/10037/4306. Last accessed September 2013.

Knust, C., Buchroithner, M.F., Dickmann, F. and Bröhmer, K. (2011) Autostereoscopic Displays for Thematic Maps. In: Proceedings of the International Cartographic Conference (ICC) 2011, 3–8 July 2011, Paris, ID: CO-270, 5 pp. URL: icaci.org/files/documents/ICC_proceedings/ICC2011/. ID: CO-270. Last accessed September 2013.

Mair, T. (2012) The Landscape Relief Model - An anachronism or a still useful object for contemplating the landscape? In: M. Buchroithner (ed.), True-3D in Cartography: Autostereoscopic and Solid Visualisation of Geodata, Lecture Notes in Geoinformation and Cartography, Springer-Verlag Berlin Heidelberg, pp 415-434.

Mair, T. and Grieder, S. (2006) Das Landschaftsrelief: Symbiose von Wissenschaft und Kunsthandwerk mit Schweizer Reliefkatalog. hier + jetzt Verlag, Baden.

Maxon Computer GmbH (2012) Cinema 4D Release 14 Quickstart Manual. Available online at www.maxon.net/support/documentation.html. Last accessed September 2013.

NOAA National Oceanic and Atmospheric Administration (2013) LIDAR – Light Detection and Ranging – is a remote sensing method used to examine the surface of the Earth. National Ocean Service (website) oceanservice.noaa.gov/facts/lidar.html. Last accessed September 2013.

Popelka, S. and Brychtova, A. (2013) Eye-tracking Study on Different Perception of 2D and 3D Terrain Visualisation. The Cartographic Journal 50/3:240-246.

ProtoCAM (2008) Subtractive Rapid Prototyping vs. Additive Rapid Protoyping. Rapid Prototyping Blog. rapid-prototyping-blog.protocam.com/2008/12/subtractive-rapid-prototyping-vs.html. Last accessed September 2013.

Rase, W.-D. (2012) Creating Physical 3D Maps Using Rapid Protoyping Techniques. In: M. Buchroithner (ed.), True-3D in Cartography: Autostereoscopic and Solid Visualisation of Geodata, Lecture Notes in Geoinformation and Cartography, Springer-Verlag Berlin Heidelberg, pp 119–134.

Räber, S. and Hurni, L. (2008) An Ambitious Relief Model Project: A Combination of a Handmade, a Computer-Generated and a Profiled Relief Model. In: Proceedings of the 6th ICA Mountain Cartography Workshop, Lenk, Switzerland. pp 185-193.

Räber, S. (2006) Handmade Relief Models. In: Proceedings of the 5th ICA Mountain Cartography Workshop, Bohinj, Slovenia. pp 222-227.

Stendel, D. (2012) Think Differently – A new Method to create Lenticular– and Integral–Pictures. In: M. Buchroithner (ed.), True-3D in Cartography: Autostereoscopic and Solid Visualisation of Geodata, Lecture Notes in Geoinformation and Cartography, Springer-Verlag Berlin Heidelberg, pp 67-81.

Stendel, D. (2013) Die neue Räumlichkeit - Visualisieren mit Linsenrastern und Papier: Beiträge zu autostereoskopisch präsentierten Planungen am Beispiel der Landschaftsarchitektur. Logos Verlag, Berlin.

Stendel, D. (2013) Personal communication. Email received on 06.09.2013.

Stilla, U. (2011) Photogrammetry and Remote Sensing - Introduction for Cartography (PRC) Lecture, 2011 Winter Semester. Technical University of Munich.

Studnicka, C., Briese, G., Verhoeven, G., Kucera, M., Zach, G., and Ressl, C. (2013) The Roman Heidentor as Study Object to Compare Mobile Laser Scanning Data and Multi–View Image Reconstruction. In: Neubauer, W., Trinks, I., Salisbury, R.B., and Einwögerer, C. (eds.,) Archaeological Prospection: Proceedings of the 10th International Conference – Vienna, May 29th–June 2nd, 2013. Austrian Academy of Sciences Press, Vienna, pp 25-28.

Szeliski, R. (2010) Computer Vision: Algorithms and Applications (September 3, 2010 draft). Springer Verlag, Berlin Heidelberg. Published online at www.szeliski.org/book/. Last accessed September 2013.

Taktikz, Inc. (2013) Additive Processes. Taktikz (website) taktikz.com/products-services/industrial-manufacturing/manufacturing-technology/additive-processes/. Last accessed September 2013.

Tomasi, C. and Kanade, T. (1992) Shape and Motion from Image Streams under Orthography: a Factorization Method. International Journal of Computer Vision (IJCV) 9/2:137-154.

Verhoeven, G. (2011) Taking Computer Vision Aloft – Archaeological Three-dimension Reconstructions from Aerial Photographs with PhotoScan. Archaeological Prospection 18 (1). pp 67-73.

Verhoeven, G. (2012) New techniques in 3D mapping: Using Structure from Motion (SfM) in aerial archaeology. Lecture slides presented at the Aerial Archaeology Summer School, Mérida, Spain, 2012.

Verhoeven, G., Doneus, M., Briese, C. and Vermeulen, F. (2012) Mapping by matching: a computer vision-based approach to fast and accurate georeferencing of archaeological aerial photographs. Journal of Archaeological Science 39:2060-2070

Verhoeven, G. and Docter, R. (2013) The Amphitheatre of Carnuntum - Towards a Complete 3D Model using Airborne Structure from Motion and Dense Image Matching. In: Neubauer, W., Trinks, I., Salisbury, R.B., and Einwögerer, C. (eds.,) Archaeological Prospection: Proceedings of the 10th International Conference – Vienna, May 29th – June 2nd, 2013. Austrian Academy of Sciences Press, Vienna, pp 438-440.

Vogiatzis, G. and Hernández, C. 2010. Chapter 12 Practical 3D Reconstruction Based on Photometric Stereo. In: Roberto Cipolla, Sebastiano Battiato and Giovanni Maria Farinella (Eds.), Computer Vision: Detection, Recognition and Reconstruction. , Springer Verlag, Berlin Heidelberg. pp. 313–345.

Welter, J. (2013) Solid Landscape Models in the Twenty-first Century – A Balanced Approach. The Cartographic Journal 50/3:300-304.

Weston, J. (2007) Desktop CNC Milling Machines and Routers How they differ. Data Wales Index & Search (website). www.data-wales.co.uk/cnc_mactype.htm. Last accessed September 2013.

Wheate, R. and Menounos, B. (2012) 3D Representation of Retreating Glaciers: Anaglyphs and the Geowall. In: M. Buchroithner (ed.), True-3D in Cartography: Autostereoscopic and Solid Visualisation of Geodata, Lecture Notes in Geoinformation and Cartography, Springer-Verlag Berlin Heidelberg, pp 315-321, 469-472.

Wheatstone, C. (1838) Contributions to the Physiology of Vision. Philosophical Transactions of the Royal Society of London, Vol. 128, pp. 371-394.

Zach, C., Irschara, A. and Bischof, H. (2008) What can missing correspondences tell us about 3D structure and motion? IEEE Conference on Computer Vision and Pattern Recognition (CVPR), 2008. Available online at www.inf.ethz.ch/personal/chzach/publications.html. Last accessed September 2013.

Zhang, G., Tsou, Y. and Rosenberger, A. (2000) Reconstruction of the Homunculus skull using a combined scanning and stereolithography process. Rapid Prototyping Journal 6/4:267-275.