# Analytical procedures for 3D mapping at the Photogeological Laboratory of the Geological Survey of Denmark and Greenland

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Photogrammetry is a classical remote sensing technique dating back to the 19th century that allows geologists to make three-dimensional observations in two-dimensional images using human stereopsis. Pioneering work in the 1980s and 1990s (Dueholm 1992) combined the use of vertical (nadir-looking) aerial photographs with oblique stereo images from handheld small-frame cameras into so-called multi-model photogrammetry. This was a huge technological step forward that made it possible to map, in three dimensions, steep terrain that would otherwise be inaccessible or poorly resolved in conventional nadir-looking imagery. The development was fundamental to the mapping and investigation of e.g. the Nuussuaq basin (Pedersen *et al.* 2006). Digital photogrammetry, the all-digital version of multi-model photogrammetry, is nowadays an efficient and powerful geological tool that is used by the Photogeological Laboratory at the Geological Survey of Denmark and Greenland (GEUS) to address geological problems in a range of projects from 3D mapping to image-based surface reconstruction and orthophoto production. Here we present an updated description (complementary to Dueholm 1992) of the analytical procedures in the typical digital workflow used in current 3D-mapping projects at GEUS.

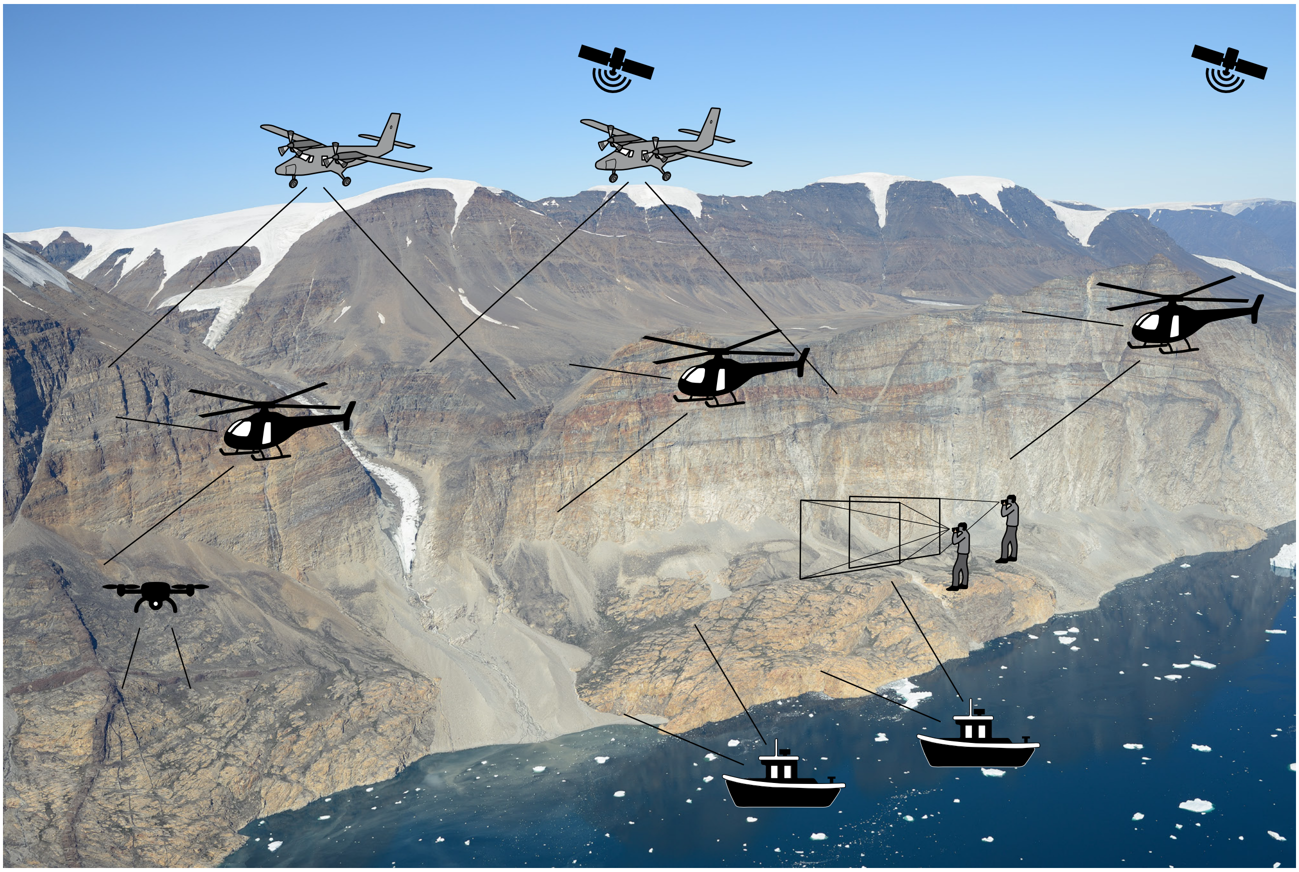

Fig. 1. During field work new stereo imagery is normally collected from helicopters or boats, but could also be collected from smaller fixed-wing aircraft, drones or while walking.

Multi-model photogrammetry in its present form is essentially a technique that allows geologists to combine stereo images of different origin e.g. from satellite, aerial or hand-held cameras, and with different resolutions and viewing angles in their geological interpretations (Fig.1), using a digital photogrammetric workstation. Examples are plentiful with scales ranging from metres (Vosgerau *et al.* 2010, 2016) to kilometres (Svennevig *et al.* 2015; Sørensen & Guarnieri 2018, this volume) or even hundreds of kilometres (Sørensen *et al.* 2017).

The strength of the methodology lies in the ability to combine stereo images with different viewing angles. Regional geological structures are e.g. typically well resolved in nadir-looking aerial or satellite images, while steep cliffs are better resolved from closer range images acquired perpendicularly to the slope of the outcrop. Essentially, digital photogrammetry allows the user to map and quantify in three dimensions whatever can be seen in the stereo images across different scales and resolutions.

The digital photogrammetric workstation described here is the modern equivalent to the analytical setup previously used at GEUS (Hougaard *et al.* 1991) and at the Institute of Surveying and Photogrammetry, Technical University of Denmark (Dueholm 1992). The workstation consists of a Windows-based computer and a split-screen 3D monitor system (Fig. 2). Technically, the monitor system displays an image of an object in one screen and an overlapping image of the same object but from a slightly different position on a second screen. A beam splitter mirror splits the polarisation direction of the two screens into separate horizontal and vertical directions. Polarising glasses used by the viewer then filter the signals so that the top screen is solely presented to the right eye and the bottom screen is solely presented to the left eye. This allows the human visual system to merge the two images, whereby a stereoscopic model is created in front of the user.

The central part of the workstation is the photogrammetric software, which is essentially a computer-controlled set of algorithms that controls the viewing of the stereoscopic model as well as the collection and manipulation of three-dimensional data within the model. This allows for seamless movement and data capture between different stereoscopic models regardless of scale, origin and viewing angle, which highly increases the speed and efficiency of geological mapping, especially in steep and inaccessible terrains.

At present, the Photogeological Laboratory uses two commercial photogrammetric 3D-mapping software solutions (*Socet GXP* from BAE Systems and *3D Stereo Blend*) that are complementary to each other in terms of technical capabilities. In the following, we describe the typical workflow used with *3D Stereo Blend*: 1) data acquisition during field work, 2) data preparation of the images, 3) data interpretation (Fig. 3). This description, however, should not be viewed as a complete manual to the software. *3D Stereo Blend* is developed by Anchor Lab in close collaboration with GEUS' Photogeological Laboratory. The software is optimised to 3D-mapping and structural interpretation using oblique stereo images collected with calibrated hand-held digital cameras. It is an essential part of the overall strategy of the Photogeological Laboratory to increase the efficiency and usability of digital photogrammetry from data acquisition to end-product, so that the method becomes a geological tool routinely used by geologists also without prior expert knowledge.

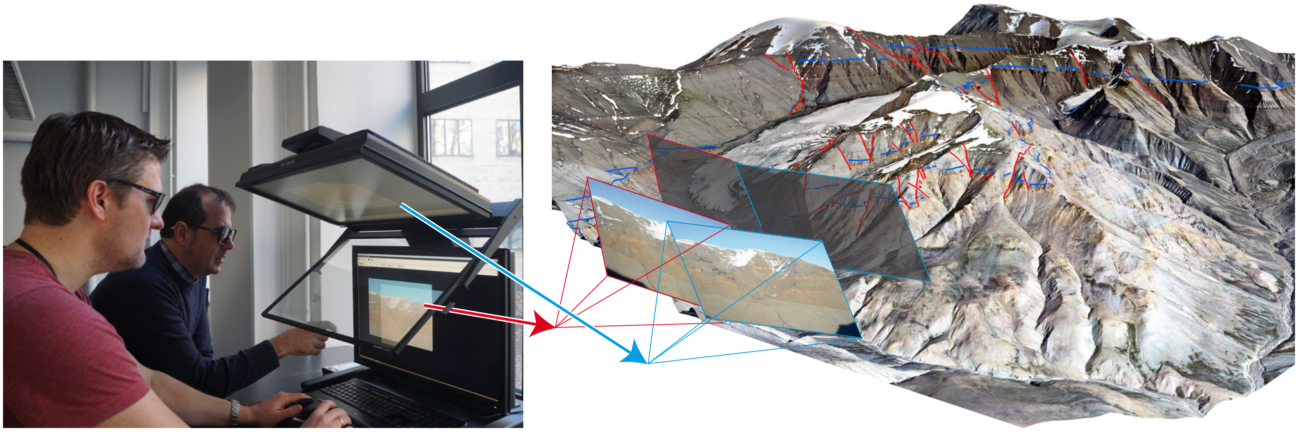

Fig. 2. The geologist at work in the Photogeological Laboratory. The stereoscopic model is displayed on a 3D monitor system that is well suited for full-day working. The stereoscopic model can be observed simultaneously by several viewers; this makes it easy to illustrate and discuss geological observations and ideas, which is beneficial for the geological interpretation.

## Data acquisition – field photography

Field work provides the geologist with important first order observations of the bedrock. Working in remote and mountainous areas such as Greenland is often challenging because of inaccessible outcrops (steep cliffs) and time constraints (short field seasons). The result is spatially scattered outcrop observations that can be difficult to correlate or relate to overall regional structures. To overcome this problem, stereo images, i.e. strips of overlapping images taken from different positions and covering the geological outcrops of interest are collected on a routine basis using hand-held digital cameras, commonly deployed from helicopters (Fig. 4). The simplicity of using a hand-held digital camera makes the data acquisition extremely mobile and fast. Furthermore, the quality, resolution and storage capacity of modern digital cameras have led to a huge increase in efficiency and capacity during data acquisition compared to the earlier days of 3D mapping. As an example, overview images of a small outcrop were collected within minutes using a helicopter, while on a more regional scale, a 100 km cliff section was photographed within less than one hour (Sørensen *et al.* 2015a). Depending on the logistic setup, the images could equally well be collected by other means (Fig. 1), as long as sufficient overlap between the images is ensured. As a rule of thumb, 60–80% overlap is needed to obtain continuous overlap and good stereoscopic measurement accuracy (Dueholm 1992). However, it is now recommended that images are taken with up to 90% overlap because this results in a more successful automatic generation of common points (so-called tie points) between different images. It will also, at a later stage, make it possible to use the images for surface reconstruction using dense image matching routines (Sørensen *et al.* 2015b). The cameras are full-frame, digital single-lens reflex with high-quality 35 mm prime lenses that are fixed and focused at infinity. However, essentially any camera can be used as long as the camera parameters (lens distortion, focal length and principal point) of the camera can be modelled. The cameras are calibrated prior to field work using a test field consisting of a steel grid with *c.* 100 points. We recommend that the images are acquired in the raw image format of the camera and that the location of the camera is registered with Global Navigation Satellite Systems (GNSS). Depending on the requirements for absolute accuracy, different GNSS equipment can be used, from simple geotagging devices to more advanced differential GNSS systems.

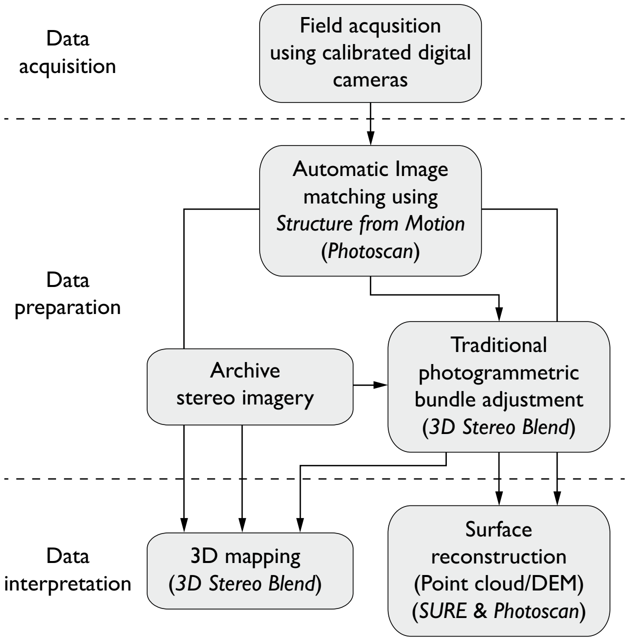

Fig. 3. Schematic flow diagram summarising the typical 3D-mapping workflow from data acquisition to photogrammetric data preparation and interpretation.

## Data preparation

Setting up the images essentially consists of two steps. First, a relative model is constructed by identifying common points (tie points) between overlapping images. Secondly, this model is transformed into absolute, 'real-world' coordinates by combining camera location data and control points.

### Relative orientation

The relative connectivity between images in object space is established by automatic tie point measurement using 'Structure from Motion' (SfM) image-matching algorithms (Lowe 2004; Snavely *et al.* 2008), with possible manual editing or addition of tie points by stereoscopic measurement within *3D Stereo Blend*. The commercial software *Photoscan Professional* (*PS*) from Agisoft is used for the image matching, but other software solutions can also be used. The raw image-matches (tie points) are subsequently exported to *3D Stereo Blend*. *3D Stereo Blend* uses the imported tie point file as a block definition and set-up file as well as for preliminary triangulation. The file is typically thinned when imported using an area-based thinning technique to give an even distribution of tie points across the images. The next step is to make a preliminary so-called bundle adjustment or triangulation, including error detection and elimination of erroneous tie points from the imported data. The images can subsequently be viewed in 3D with the orientation of that exported from *PS*. If positional data, such as e.g. GNSS camera positions, are included in the export from *PS*, the stereo-

Fig. 4. Stereo images collected from helicopter using a hand-held digital camera. This method makes the data acquisition very mobile and fast. The location of the camera is registered with Global Navigation Satellite Systems. Photo: Jonas Petersen.

scopic model will be placed in absolute coordinates within *3D Stereo Blend*. Depending on the project requirements, one could move directly on to the 3D-mapping stage for rapid results or if absolute accuracy is of minor importance. However, requirements for absolute accuracy often mean that additional control data must be added.

### Absolute orientation

The absolute orientation relates the photogrammetric models in object space to absolute coordinates through a proper bundle adjustment process, whereby the stereoscopic model gets the correct scale and levelling. When solving the bundle adjustment, all provided control information is weighted according to an *a priori* estimated error. Different sources of control data can be used in this process, including surveyed control points, pass-points, camera GNSS-data, planar levelling points and distances. Surveyed ground-control points generally give the best positional accuracy. However, considering the regional scale of many 3D-mapping projects, this approach is often not viable from a practical point of view. Instead, pass-points from already aerotriangulated aerial photographs can be used as control-point source, which eliminates the need for ground-control-point collection during field work. This is done by identifying common points between for example a set of vertical aerial photographs and local oblique-view images. This process is sensitive due to the different perspectives of the image data sets as well as the different resolutions, and takes some practical experience to carry out. However, workflows implemented within *3D Stereo Blend* have significantly improved the efficiency of the identification process. GNSS data collected with the camera yield the position of the camera at the time of acquisition that is important for setting up the images. Simple geotagging equipment typically yields a camera position accuracy of around 5–10 m. However, more advanced differential GNSS set-ups could result in a positional accuracy at the sub-metre level, which might minimise or completely eliminate the need for surveyed ground- control points or measured pass-points.

The overall time consumption in the preparation of the images has significantly decreased compared to the early days of analytical 3D mapping. This is largely a consequence of computer hardware and digital camera development, but also of software improvements including better image-matching algorithms and improved photogrammetric workflows in the *3D Stereo Blend* software. Consequently, small blocks of stereo images can be prepared for geological interpretation within a day. This opens up for e.g. using digital photogrammetry as an active tool during field work.

## Stereoscopic image interpretation – 3D mapping

Once the images are properly prepared, or if archive data are available, the geologist can commence the geological photointerpretation in three dimensions. This is done by tracing geological features of interest in the stereoscopic models. The change between neighbouring stereo models takes place automatically, so that important horizons can be traced seamlessly for kilometres. Several views can be opened simultaneously, whereby an outcrop can be seen from different perspectives and at different resolutions, which is important for the geological interpretation. The different views can furthermore be linked, so that a movement in one window is also updated in the linked window. Changing the displayed stereo block is either done by selecting from a pull-down window or by selecting the cameras in perspective view interactively. All images from the cameras within a project can be shown in the perspective view. This makes it easy to manage and move around in large regional data sets with thousands of images. The outcome of the drawing is a number of vectorised lines in 3D with many nodes (so-called polylines) superimposed on the stereoscopic model (Fig. 2). The polylines can be labelled and grouped according to the user's need, and subsequently exported to GIS packages for GIS analysis or to 3D-modelling software. The software automatically registers the original stereo model in which each node of a given polyline was drawn. This makes it possible to automatically adjust the images if their orientation is changed at some point. This is helpful e.g. if an initial interpretation of the images is done on a preliminary set-up of the images without proper ground control.

A central part of the *3D Stereo Blend* software is a set of structural tools that enables the viewer to evaluate structural parameters such as strike and dip of bedding, plunge and direction of fold axes and stratigraphic thickness of beds. This allows the geologist for instance to populate a geological map with many structural observations from areas that could not be visited in the field, to correlate bedding from one side of a fjord to the other or to measure true thicknesses. The structural tool-set consists of selected routines from the *Geoprogram* software (Dueholm & Coe 1989) and works by fitting planes by least-squares adjustment of captured data points. Of special importance is the possibility to project captured data into geological sections which can have arbitrary orientations and also be inclined to better reflect e.g. true thicknesses.

In summary, with the present set-up, 3D mapping has become much more effective and user-friendly than previously, which is largely due to the improved photogrammetric workflows in the *3D Stereo Blend* software. For instance, it is now possible for the untrained geologist to engage in 3D mapping with only 1–2 days of training.

## Resolution and accuracy

The resolution of the stereoscopic models depends on the distance between the camera and outcrop, the camera focal length and the pixel size (pixel pitch) of the sensor of the digital camera. As an example, photographing an outcrop at a distance of 100 m gives a ground sampling distance (GSD) of 14 mm using e.g. a 36 megapixel *Nikon D800E* camera with a calibrated sensor pixel pitch of 4.89 µm and a focal length of 36 mm, or a scale of *c.* 1:3000, while increasing the distance to 1000 m will give images with GSD of 0.14 m (scale 1:30 000).

The photogrammetric or geometric accuracy in the image plane on the ground (the x and y axes perpendicular to the direction of view) relates to the distance between the camera and outcrop, the camera focal length and how accurately a point can be determined in the stereoscopic model. The latter is a function of the accuracy of the triangulation, the camera calibration and on how well the user can place a point in the stereoscopic model. In addition, the photogrammetric accuracy in depth (the z axis, in the direction of view) also depends on the ratio between the distance between the camera and the object and the distance between the camera stations (also called the baseline). A typical value for the point determination is around one pixel, which leads to an accuracy of *c.* 14 mm in the image plane, while the accuracy in depth is *c.* 35 mm with a distance to the outcrop of 100 m and a baseline of 40 m (corresponding to 60% overlap). If the camera-to-object distance is increased to 1000 m, the accuracy in the image plane decreases to 0.14 m, while the accuracy in depth will decrease to 0.35 m, assuming that the baseline is increased to 400 m to maintain a 60% image overlap. However, if the baseline remains 40 m long there is a significant decrease in the depth accuracy to *c.* 3.5 m. This illustrates the importance of having an appropriate image overlap.

The absolute accuracy of the stereoscopic model relates to that of the control source. In Greenland, pass-points are commonly acquired from the monochrome vertical aerial photographs on a scale of 1:150 000 that cover most ice-free areas. Typical achievable accuracies on the point transfer from these photographs is around 3–5 m. Using high-precision differential GNNS setup it should be possible to obtain accuracies of less than 1 m, whereby the absolute accuracy approaches the photogrammetric accuracy.

Although the absolute accuracy generally exceeds that of the photogrammetric accuracy, the relative accuracy between models remains equal to the photogrammetric accuracy, because the ground-control data is weighted during the bundle adjustment. This means that when calculating e.g. thicknesses or structural parameters such as strike and dip, the accuracy is determined from the photogrammetric accuracy. In practice, this is all handled automatically within the *3D Stereo Blend* software.

## Other derived products

In addition to the 3D geological mapping workflow, the technical development of automatic multi-view- stereo-matching routines (Rothermel *et al.* 2012) has facilitated the extraction of digital outcrop models from stereo imagery (Sørensen *et al.* 2015b). The digital outcrop model is a 3D representation of the outcrop surface. This type of routine utilises the redundancy of high image overlap to produce a set of high-resolution data points in space (so-called point clouds) that need little manual editing. Although a high image overlap (i.e. a small baseline) reduces the precision of individually matched pixels, this is compensated by determining the same point in multiple images, which leads to effective automatic elimination of erroneous points. The point cloud is used e.g. for visualisation purposes where it can be integrated with the results of the 3D geological mapping, but it can also be further processed into 3D mesh representations of the terrain, or production of digital terrain models and orthophotos. GEUS' Photogeological Laboratory is currently using a suite of software solutions for terrain extraction. Software such as *Photoscan Professional* from Agisoft and *SURE* from Nframes is typically used in the digital outcrop model workflow, while more conventional aerial and satellite imagery is processed using *Socet GXP*.

## Summary

The all-digital version of multi-model photogrammetry, now referred to as digital photogrammetry or just 3D mapping, has brought the geological outcrop into GEUS' Photogeological Laboratory. The recent increases in efficiency all the way from data acquisition to the geological interpretation makes 3D mapping an attractive geological tool available to the geologist. With a digital photogrammetric workstation, the users can view, map and explore any geological feature in three dimensions, following the principle that whatever can be seen in the images can also be mapped and quantified in 3D.

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