OBLIQUE HELICOPTER-BASED LASER SCANNING FOR DIGITAL TERRAIN MODELLING AND VISUALISATION OF GEOLOGICAL OUTCROPS

S. J. Buckley[1, *], J. Vallet[2], A. Braathen[3], W. Wheeler[1]

[1]Centre for Integrated Petroleum Research, University of Bergen, Postboks 7800, N-5020 Bergen, Norway - simon.buckley@cipr.uib.no, walter.wheeler@cipr.uib.no
[2]Helimap System, CH-1066 Epalinges, Switzerland - vallet@uwrsa.ch
[3]University Centre on Svalbard, N-9171 Longyearbyen, Norway - alvarb@unis.no

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ABSTRACT

Terrestrial laser scanning is becoming increasingly popular for modelling geological outcrops, because of the high resolution, accuracy and ease of dataset integration. Despite these significant advantages, limitations with the technique remain when the spatial extent of the study area is large, as most current systems have a maximum range of less than one kilometre. This becomes a major problem when outcrops are high, as the scanner cannot be positioned far enough away to provide a good angle of view, making data quality poor. This paper reports on a novel use of lidar in geological outcrop modelling, using a helicopter-based system that can be mounted obliquely to allow steep and vertical cliffs to be captured from an optimal scan angle. Use of a helicopter-based system results in large amounts of data, because of the very large areas, which are difficult to process and visualise using available software. In particular, building a 3D mesh from the raw point data, and performing texturing mapping, using a high enough resolution to be able to accurately interpret geology, is difficult. Multiresolution modelling and specialised viewing software was therefore required to process the 3D data into separate levels of detail and create the texture mapped virtual outcrop model. Despite the large volumes of data, the processing workflow presented here allowed textured models with tens of kilometres extent to be loaded simultaneously for interpretation and visualisation by geologists, as well as for integration with geophysical data. The use of the helicopter-based lidar and camera system allowed otherwise inaccessible outcrops in a harsh environment to be studied, with higher quality output than previously possible.

1. INTRODUCTION

A paradigm shift is currently occurring in many fields of the geosciences, as digital spatial data collection techniques become more widespread, with the associated accuracy and resolution allowing more detailed and quantitative analysis to be carried out (e.g. McCaffrey et al., 2005). One such growth discipline is geology, especially the study of outcrops, where areas of exposed rock can be used to help understand subsurface processes (Bellian et al., 2005; Buckley et al., 2006). Of particular interest is the study of analogues – outcrops that have similar properties in terms of depositional architecture, bedform geometries, preserved stratigraphic architecture and fault zone geometry, as subsurface hydrocarbon reservoirs. These analogues can be examined in situ by the geologist, and field data acquired for use in subsurface reservoir modelling. Using laser scanning, collected point clouds are processed to form digital terrain models, which are then textured with simultaneously acquired digital imagery. This results in a virtual outcrop model that can be used for interpretation, digitisation and quantitative analysis of the geology (Buckley et al., 2008).

With the introduction of terrestrial laser scanning to the geology discipline, the advantages in terms of accuracy and spatial resolution are allowing an increasing number of studies to focus more on quantitative research problems, in a way that was impossible using traditional field data alone (e.g. Sagy et al., 2007; Enge et al., 2007). However, when the geological outcrops are large, limitations with terrestrial scanning are apparent that make the technique unsuitable. Most current lidar technology allows a maximum range of one kilometre or less for natural targets (e.g. Optech, 2008; Riegl, 2008), having implications on the success of acquiring data for large, high outcrops. In addition, over wide areas (greater than 1 km^2) the application of a ground-based method becomes inefficient in terms of field time, and results in a large amount of data being acquired.

To provide the best quality virtual outcrop, input data should be captured from as close to perpendicular to the topography as possible. For the lidar data this is less important, though if the angle between the outcrop face and the sensor is too extreme, a poor point distribution and holes will result. However, for the imagery the obliquity is critical, as very oblique data gives a poor visualisation when textured on the surface model. With a poor quality virtual model, it is extremely difficult for geologists to undertake interpretation.

In this research a helicopter has been used as the platform for lidar and image collection, getting round the viewpoint problems described above. A helicopter provides the perfect platform, as it is manoeuvrable and can be flown to follow the actual topography. With an oblique lidar and camera system, data can be captured normal to the outcrop, giving good processing results. In addition, because of the rapid data acquisition it is possible to cover wide areas and high cliffs in much shorter time than when using a ground-based scanner.

* Corresponding author.

Use of a helicopter-based system results in large amounts of data, which are difficult to process and visualise using current software and hardware. Using the point cloud alone it is not possible to distinguish small features, even with dense point spacing; image data is therefore integrated and used to give extra detail by performing texture mapping (Buckley et al., 2008). However, building a 3D mesh from the raw point data, and performing texture mapping is difficult for large datasets, whilst maintaining a suitable size of resulting model that can be loaded in memory on current computing hardware. For outcrop modelling, it is also important for the geologist to be able to load large areas, often the complete study area, to obtain an overview, as well as to focus on fine details at large scale in the same viewing session.

The two problems are therefore related: using a helicopter-based acquisition platform results in large datasets covering wide areas, requiring a more sophisticated processing and visualisation strategy to be developed to allow the geologist to be able to view and interpret the whole area at the desired level of detail. This paper outlines the data collection for a large field area, as well as the approach developed for creating multiresolution models of large outcrops.

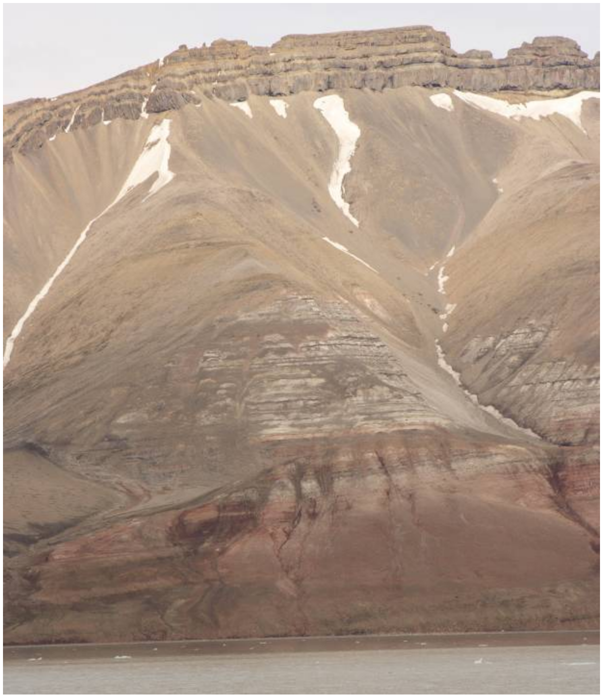

Figure 1. Part of Wordiekammen, showing karst rock on top and gypsum layers below. Outcrop *c*. 850 m high.

2. STUDY AREA

The study area for this research is the Billefjorden region of Svalbard (Spitsbergen), Norway, where excellent exposures of large carbonate outcrops exist. These outcrops contain laterally extensive paleokarst surfaces, where collapsed features such as caves have left large breccia-filled pipes. The area is of relevance geologically, as it is a direct analogue to the subsurface of the Barents Sea, a potentially important region for hydrocarbon production, and allows surface study of similar environments (Eliassen and Talbot, 2005).

However, the outcrops are large: with heights of over 800 m, tens of kilometres lateral extent, and near-vertical cliffs of several hundred metres, some sides surrounded by water, these outcrops would have been impossible to capture using a terrestrial laser scanner. In addition, the field area lies at approximately 78º North, deep within the Arctic Circle, and approximately 60 km from the nearest habited settlement. For this reason, survey logistics are difficult and the “snow-off” field season short. A detailed study of one area of Billefjorden is ongoing, at Wordiekammen, a mountain on the West side of the fjord (Figure 1). Here, digital spatial data of the topography of the outcrop is being combined with geophysical (ground penetrating radar) data from inside the outcrop to form a detailed, true 3D model of the geology to be used to help understand the potential effect of the paleokarst features on fluid flow.

3. SYSTEM USED

A laser scanner and high resolution digital camera were integrated with an inertial measurement unit (IMU) and Global Positioning System (GPS) in the proven Helimap System, and mounted onboard a helicopter. The Helimap System is described in detail in Vallet and Skaloud (2004) and Skaloud et al. (2006), and consists of the following components:

1. Riegl LMS Q240i-60 airborne laser scanner;
2. Hasselblad H1 22 mp camera with 35 mm lens;
3. iMar iIMU-FSAS inertial measurement unit;
4. Dual frequency GPS.

The system is able to be mounted on a number of helicopters, and takes only a short preparation time to be ready. The helicopter used for the Wordiekammen mission was an AS350B (Figure 2). Accurate boresight and camera calibration established the spatial relationship between the system components, to ensure a good registration between the 3D data and the digital imagery. The boresight calibration was controlled during the mission, using a flight over ground targets at the airport close to the main town of Longyearbyen.

Figure 2. Helimap System mounted on AS350B helicopter.

The system is unusual in the fact that it may be mounted to look obliquely, as well as in the conventional nadir-looking configuration. For the steep outcrop cliffs and slopes to be modelled in this research, the oblique configuration offered the optimum data collection solution, where a standard airborne laser scan would have left the vertical areas poorly covered, as well as degrading the accuracy of data points at the edges of the swath (Vallet and Skaloud, 2004).

4. DATA COLLECTION

The data collection mission occurred in August 2007, in the middle of the Arctic summer. Prior to flying, important mission planning was performed to determine the times when the GPS constellation was at its best geometric configuration. Because of the proximity of Svalbard to the North Pole, there were several periods within a 24 hour period where poor satellite geometry existed (marked by degradation in positional dilution of precision – PDOP – as well as number of satellites available). These areas were avoided for data collection to achieve the best measurement precision of the system. Fortunately, in the far North, daylight lasts for 24 hours, making it easy to avoid the poor GPS periods without losing valuable time.

Prior to the collection of scan and image data, two GPS base stations were positioned within the field area. These were used to position the helicopter-mounted GPS, and in turn were positioned relative to a base station operating on a fixed point in Longyearbyen.

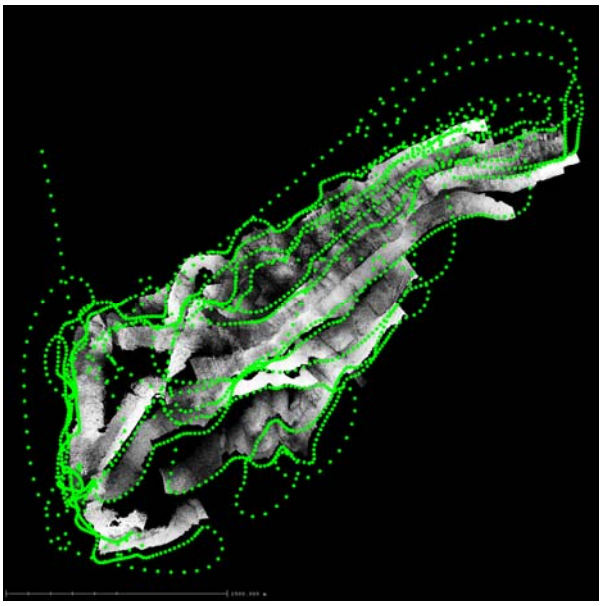

Figure 3. Plot of GPS flight trajectory for Wordiekammen, superimposed over laser point cloud.

The mission for Wordiekammen took around three hours of flying, not including the travel time and the time needed to setup the GPS base stations. Once the mission was begun, alignment of the inertial systems was required. This was achieved by flying on a constant heading for one minute, before performing 360º turns at maximum velocity in order to get horizontal acceleration (Skaloud, 1999). A similar turn was repeated at the end of each flight line to realign the gyros which systematically drift over time. For the data collection, the helicopter pilot was directed to the start of a flight line, at a distance of around 300 m from the terrain, or the maximum range for the scanner used where all surfaces provide laser reflection. Once the helicopter was on the flight line, laser, GPS and inertial data were recorded constantly, and the camera triggered by the operator.

The Helimap System is flexible in that it is handheld by the operator (with load supported by a frame) so that it may be pointed to maintain an angle perpendicular to the local topography, resulting in the best quality laser and image data. Once a flight line was finished, the 360º turn was repeated and the next line begun. For the highest parts of Wordiekammen (850 m), up to five strips were required, with a degree of overlap for checking the consistency of individual strips (Figure 3). Images were also collected with 70% stereo overlap to allow the potential for complementary stereo-plotting.

5. DATA PROCESSING

5.1 Raw Point Cloud Processing

GPS data were first processed to establish the base station coordinates relative to the fixed point in Longyearbyen. One of these was then used to fix the trajectory of the GPS on the helicopter, with the second available in case of hardware failure. Once the GPS data were processed, the point cloud could be determined by processing the time stamps of GPS, inertial and laser data to obtain first the positions and orientations of the laser measurements, and secondly the coordinates of the points. Similarly, the positions and orientations of the camera centres were found using the time stamp of the image and GPS/INS data.

The overlapping flight lines were compared for systematic errors and, if necessary, adjusted (Crombaghs et al., 2000). Very occasionally, laser profiles showed gross errors, possibly caused by poor GPS positioning at that epoch, and had to be removed. Overall accuracy of the system reached 0.10-0.15 m. Because of the large size of the area and rapid measurement speed of the laser scanner (10 kHz), the raw point cloud was extremely large, consisting of tens of millions of individual data points. However, because the point density was much greater than the relative point precision of the system, random noise existed in the raw data that was undesirable for terrain modelling, and would have resulted in an unrealistically rough surface being formed. The raw point cloud was intelligently thinned and smoothed according to the localised gradient, to leave a reduced point cloud where the density was greatest in the areas of most surface roughness (i.e. the geology rather than the smoother scree slopes).

5.2 Mesh Creation

The thinning of the original point cloud from tens of millions of points to *c*. 8 million resulted in a more manageable dataset. However, for geological interpretation it was unsuitable, as the details of the geology could not be seen within the relatively sparse points (around 1.5 m point spacing). Therefore it was required to triangulate the points to form a digital terrain model (DTM), which could then be mapped using the additional metric imagery. The resulting textured model would have higher resolution due to the resolution of the imagery (smallest distinguishable feature approx. 0.2 m). The main problem associated with the use of lidar presented itself here, in that to create a textured model of the whole area would either require reducing both the triangle count and the image resolution, or split the area into many small chunks that could be processed and loaded separately. The first would allow the whole area to be viewed at once, but would only give an overview; when zooming in, the resolution would be too poor to determine small features. The second method would allow the details to be interpreted, but it would not be possible to gain an overview of the whole area in the same viewing session, as limitations on hardware allow only a fraction of the full resolution data to be loaded. Additionally, splitting the whole area into smaller areas requires additional laborious and time consuming processing, and much care given to data management.

Instead, the approach developed here aims to allow both methods simultaneously, by creating a hierarchical set of level of detail (LOD) models and a spatial segmentation of the whole area to allow the creation of a paged database that can be handled by viewing software to load the required data resolution according to object-to-screen distance. Such an approach has been developed within the computer vision field (El-Hakim et al., 1998; Borgeat et al., 2005), and is implemented in its simplest form for 2.5D data, such as within the Google Earth software. For true 3D data containing vertical cliffs and overhangs, the procedure is more complicated, and more sophisticated meshing and texture mapping algorithms are required.

The thinned point cloud was meshed in the PolyWorks software, using all the available points. No smoothing or decimation was performed, as this had already been performed on the raw point data. This mesh represented the highest available resolution.

5.3 Spatial Segmentation

The highest level mesh was segregated into an octree structure (Figure 4), where the octree was created to allow a maximum of 1000 triangles in a particular node. The maximum number of triangles per node was determined empirically as a suitable amount of textured geometry to store in a single file on disk allowing fast paging during the real-time viewing of the 3D model. The maximum depth of the octree determined the number of LODs that would be created to fill each level of the octree.

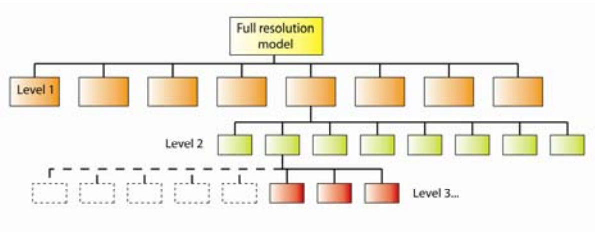

Figure 4. Schematic of octree structure.

For each level in the octree above the last level (corresponding to the available highest resolution mesh), the original mesh was decimated to produce the LOD models. The criteria for decimation were based on: the maximum error between the original mesh and the decimated mesh; the maximum allowable edge length of a triangle; and a target compression rate, given in percentage of the original model to keep (see e.g. Schroeder et al., 1992 for a similar implementation). For each level, the compression target was set to 60% of the number of triangles in the previous level. This meant that the levels were progressively coarser in resolution until the top level, which formed the first and overview model. This overview model was compressed to a slightly higher level to ensure that not too much memory was allocated to this basic model by the viewing software. Once the LOD meshes were built, the octree was traversed from bottom (finest) to top (coarsest), filling each node with triangles from the corresponding LOD level, or original mesh in the case of the bottom level of the octree. Instead of storing the geometry for each node in memory, each node was temporarily written to disk, a filename stored in the parent node, and a flag set to show that the node had been processed. When the parent node was processed further on in the algorithm, a check was made to see if all the possible (eight) children had been flagged as processed, and if so the temporary files were loaded and written again to a single file, with filename stored in the parent node. In this way, the memory footprint of the algorithm was kept very low, only requiring that the original resolution mesh to be stored in memory, as well as temporary variables for processing a current node. Although, reading and writing temporary data files caused additional processing time, larger datasets were able to be handled by the algorithm.

As each parent node was processed, two range values were also stored relating to the distance between the viewer camera position and the bounding box of the node. The ranges determined the swapping position of the current node and its eight children. When each node above the last was written to disk, the geometry of the node was written, as well as a filename linking to the file containing the child geometry. In this way, the octree structure was recreated on the hard drive of the processing computer, and used later on during visualisation. Figure 5 shows the octree-partitioned terrain model, highlighting the comprising surface patches in different colours for clarity.

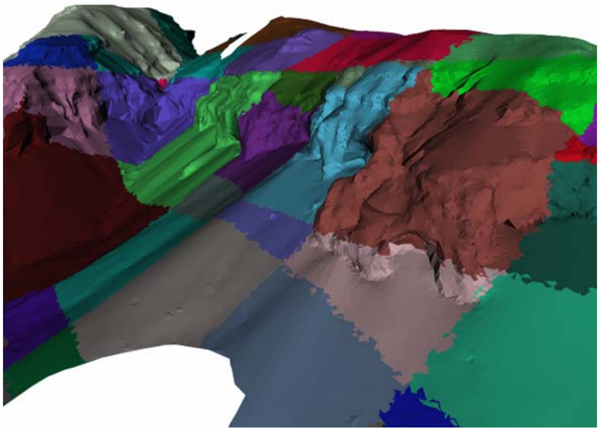

Figure 5. Octree partitioned 3D model of Wordiekammen (approx. 1000 m × 500 m × 600 m).

5.4 Texture Mapping

The above section details the creation of the 3D model component of the outcrop; however, it is still not in a form interpretable by geologists, except for purely geometric studies, such as measuring thickness of layers, making cross sections and measuring components such as surface strike and dip. To be able to make quantitative measurements of features in the cliff faces, such as layers, that may have little or no 3D qualities (i.e. the cliff may be smooth), the image data must be used. Texture mapping the 3D model data then allows both additional quantitative measurements to be made, as well as more qualitative geological interpretations.

The image data was searched to find the images whose projection in space contained part of the 3D model to be mapped (Figure 6). Because of the high overlap created by stereo capture, a large number could be discarded to reduce the input to the texture mapping algorithm. Each image used had lens distortion effects removed before creating texture maps. Because individual triangles could potentially have a number of available images to choose, determined by the collinearity condition, criteria were chosen to find the most suitable image. These criteria included the distance from projection centre to triangle centre, the area of the triangle in the image, the angle between the camera ray and the triangle normal, and whether or not intersections with the rest of the model occurred between the projection centre and the triangle. Some of these parameters are discussed further in e.g. El-Hakim et al. (1998).

Figure 6. Detail of Hasselblad H1 image.

During the filling of the octree levels with geometry data, each texture mapping was also performed. A pre-processing stage identified the best image for each triangle, according to the criteria above, before the imagery was processed to create texture maps and determine texture coordinates for each triangle. Prior to creation, the image was scaled to a proportion similar to the compression rate of the corresponding mesh data for the octree level being processed. The texture map was written to disk along with the geometry data, and could be compressed to save disk space if desired. This completes the algorithm description for creating high-resolution texture mapped multiresolution models from the lidar and photogrammetric data.

6. RESULTS

The Wordiekammen point cloud was segmented into seven sections to simplify image identification and mesh processing. This was required to ensure that enough memory was available for processing approximately two million points into a surface model (on a 32-bit machine; moving to a 64-bit processor would mean that the whole model could be processed at once). Each of the seven segments was processed as described in Section 5, and the resultant model data saved to disk. Some 10,000 files and 15 gigabytes of data were stored (with compressed textures). Table 1 outlines key parameters of the dataset.

Wordiekammen dataset	
Number of data points used	*c*. 8 m
Number of triangles in top level	*c*. 16 m
Number of levels	9
Number of images	*c*. 500
Average point spacing	*c*. 1.5 m
Size of area	7 km × 3 km × 800 m
Size of data on disk	15.4 Gb

Table 1. Parameters of the Wordiekammen dataset.

The data were loaded in viewing software designed to handle such paged databases (Figure 7), and running on a standard high-end laptop with a reasonable graphics card obtained frame rates during visualisation of around 60 frames-per-second (fps). Small hits in performance were noted if the user moved too fast around the model, causing a large amount of data to load at once. However, this was minor and the visualisation was more than adequate for viewing at interactive speeds. Some further work will be carried out on determining the optimum parameters for the data paging system. Some deterioration of the texture quality occurred in areas where a number of images were available for mapping, as adjacent triangles were assigned different images, disturbing the realism of the model where varying photographic lighting conditions and view angles existed. Much research has been reported on alternatives to handle these localised effects (e.g. El-Hakim et al., 1998; Rocchini et al., 1999), and improvements can be made to the texture mapping pre-processing stage used reported here.

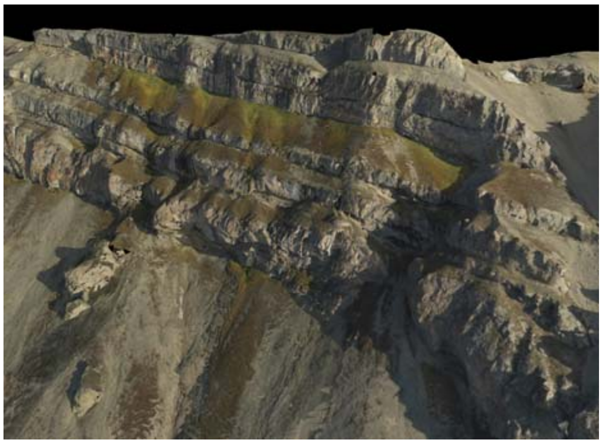

Figure 7. View of textured 3D model of paleokarst layers at Wordiekammen. Height of scene approx 400 m.

7. CONCLUSIONS

This paper has described the collection and processing of oblique helicopter-mounted laser scanning and image data for large geological outcrops in the islands of Svalbard, Norway. The Helimap System utilised proved to be the most efficient means of collecting detailed topographic data for these large outcrops, with the detail required by geologists. Where a ground-based scanner would have been unsuitable, because of the insufficient range and high obliquity, the helicopter-mounted system could maintain a normal view to the actual topography, with high 3D point precision and image quality.

The use of such a system and acquisition over large areas created very large volumes of data, making processing and visualisation an issue. The multiresolution modelling approach presented enabled the data to be visualised at interactive frame rates and, with just one master model file to load, it is therefore extremely easy for geologists to use for research and training.

With the final virtual outcrop processed, it is available for interpretation and visualisation by geologists, as well as possible to integrate geophysical data collected at the same time. The use of the helicopter-based lidar and camera system allowed otherwise inaccessible outcrops in a harsh environment to be studied, with higher quality output than previously possible.

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