Digital Elevation Model Reconstruction of a Glaciarized Basin Using Land-Based Structure from Motion

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ABSTRACT: In a climate change context, volume variations of glaciers can be efficiently evaluated by comparison of Digital Elevation Models (DEM) of the ice surface, taken at different time frames. However, traditional methods of DEM reconstruction lack either in resolution or they are costly, considering the remoteness of certain basins. This study aims for testing a method called Structure from Motion (SfM) for high resolution DEM reconstruction on a 2.7 km^2 glaciarized basin in the Aqqutikitsoq mountain range, Western Greenland. The SfM method is capable to recreate the 3D structure of an object using a set of highly overlapping pictures covering the entire surface of the object itself. This concept is applied to the Aqqutikitsoq glacier, which was mapped using a consumer grade camera in August 2014. The 3D model was obtained by processing with the software Agisoft Photoscan 249 pictures taken from four main viewpoints. The georeferencing was done using 50 Ground Control Points (GCPs) acquired during the ground survey. The GPS coordinates of the GCPs were obtained using a Post Processing Kinematic (PPK) method, which reaches centimeter precision. The results show that the glacier surface is mapped with a resolution of 0.79 m and a elevation accuracy of 0.73 m. Considering the level of the equipment involved, the high resolution achieved, the logistic and technical ease of the method, it can be stated that SfM represents a powerful and efficient technology for DEM reconstruction suitable for glaciers located in remote areas.

KEY WORDS: Structure from Motion, Geodetic mass balance, Digital Elevation Model, 3D Reconstruction, Georeferencing.

1 INTRODUCTION

The sensitivity to climate change is demonstrated to be higher for Greenland coastal glaciers than for the Greenland ice sheet (Bolch et al. 2013). However, 70% of the electricity in Greenland is produced by hydropower plants whose hydrological water balance is influenced by the melt water from coastal glacier (Ministry of Foreign Affairs of Denmark, 2013). Therefore, the monitoring of those glaciers is needed to predict the effects of climate change on the availability of glacial melt water.

In order to quantify the melting rate of a glacier the mass balance has to be determined. In general, the mass balance of a glacier is the change of the glacier mass over a given time span. One approach to evaluate the mass balance is called the geodetic mass balance and is based on measuring the differences in height and horizontal extent of the glacier surface at different points in time. The surface of the glacier is represented by a Digital Elevation Model (DEM), a georeferenced grid of elevations which samples the real topographic surface. By comparing glacier DEMs acquired at different times, it is possible to evaluate how the ice surface and, by consequence, the ice mass changed over that time span. The total volume of the glacier can also be evaluated in order to calculate the variations in terms of percentage of the total mass (Moholdt et al. 2010). This is done using Ground Penetrating Radar (GPR), a geophysical method to measure the thickness of the ice along cross sections of the glacier. The cross sections can be interpolated in order to obtain the DEM of the bedrock. The difference between surface and bedrock DEMs gives the ice volume of the glacier.

The methods used to acquire DEMs, can be grouped in three categories: satellite imagery, airborne photogrammetry and Light Detection and Ranging (LiDAR). The state of art of using satellite imagery for DEM reconstruction is overviewed by Dietz et al. (2011). In general, DEMs reconstructed with satellite imagery have low resolution and the dataset needs to be validated with ground surveys. Airborne photogrammetry is frequently used in DEM reconstruction applied to glaciology (Fox & Nuttall, 1996). However, this method is expensive considering equipment and logistic, a factor which is amplified in remote areas. This problem applies also to LiDAR scanning, although successfully used in glacier DEM reconstruction, according to Hannesdottir et al. (2013), Belart et al. (2013) and Gudmundsson et al. (2013). Therefore, it can be said that while DEM acquisition nowadays possesses various established methods, high resolution datasets are seldom available and can involve high costs, especially in remote areas.

In the present paper a method called Structure from Motion (SfM) is used to derive a DEM of a glaciarized basin. The SfM method is capable of obtaining 3D models from 2D images based on the same concept which allows humans to recover 3D space from the projected 2D (retinal) motion field of a moving object or scene. Although mostly known in others fields, as archeology and architecture, SfM applied to DEM reconstruction was tested and validated by Westoby et al. (2012) showing that this technology achieves the same resolutions and accuracy as LiDAR scanning while using consumer cameras and differential GPS systems. The process is cheaper and easier to apply in comparison with other methods. However, the method has not been established for glacier surface reconstruction, which poses specific challenges. The derivation of a suitable DEM could provide a powerful tool for DEM generation for these kind of application.

The paper illustrate how a DEM of the Aqqutikitsoq glaciarized basin located in West Greenland was obtained using Structure from Motion. The aim is to provide a general workflow of the method by describing the work performed during a field campaign in the selected area and to validate the quality of the DEM obtained. The resulting DEM will be used in further studies to calculate volume change of the glacier in combination with preexisting DEMs.

2 MATERIAL AND METHODS

The basic concept of SfM technology is the reconstruction of a 3D model of an object from a set of overlapping pictures of the object, taken from different points of view.

The SfM workflow is divided in three steps: pictures acquisition, GCPs survey and DEM generation.

2.1 Pictures Acquisition

The first step is the acquisition of the pictures of the object. This step can be done with any kind of digital camera. However, the best outcome can be achieved when the pictures have high resolution e.g. high amount of features and details. Thus, the camera specifications to be considered are those increasing the resolution of the pictures, e.g. the pixel size of the sensor and the optical qualities of the lens. In the present paper, the pictures were acquired using two entry level SLR cameras: Nikon D3100 with a Sigma 10-20 f/4.5 lens mounted, and Nikon D3200 with the standard Nikon 18-55 f/3.5 lens.

Since the reconstructing algorithm recognizes identical points in the overlapping areas to align the pictures, the rule of thumb is to avoid features that lead the software to matching point's misclassification e.g. excessive perspective. In the present paper, the survey was made in a mountainous environment. Thus, the amount of viewpoints was large enough to ensure a good perspective of the glacier.

2.2 GCPs Survey and post-processing

The GCPs survey is the location of noticeable features of the object using a global positioning system (GPS). These points are GCPs can be either artificial or natural (Westoby et al, 2012). The accuracy of the GPS is reflected in the accuracy of the georeferencing of the 3D model. The optimal georeferencing is achieved when the distance error from the 3D model point and its real coordinates is minimized. Thus, the GCPs need to be as many as possible and evenly distributed in order to avoid fitting errors.

Post processing kinematic (PPK) is used as field procedure for acquiring the GPS coordinates. This method is based on the acquisition of the data by a moving rover antenna which was carried around the control points acquiring the GPS coordinates and the use of a reference base station data. The reference base station has to be located at least within 30 kilometers from the rover antenna. The method has the advantages of being quick and achieve centimeter precision. It consists in the acquisition of rapid static measurements of the desired points, which lasts around 5 seconds per measurement, together with continuous kinematic acquisition of other satellite data when moving from point to point. The equipment used in the fieldwork is a Trimble 5700 receiver combined with a Zephyr 4-point feed antenna as roving receiver and the Sisimiut Geodetic Reference station as the base station.

In PPK surveying the rapid static and kinematic data obtained during the fieldwork has to be calibrated with base station data which consists in carrier phase and code range measurements in order to support the three dimensional positioning. This data improves the precision of the coordinates acquired. Reference Stations are continuously acquiring the information, therefore the data needed has to be extracted for the same day the fieldwork measurements were acquired. In this case the Sisimiut reference station data was used and it was provided by the Danish National Space Institute (DTU Space) in RINEX format. In order to perform the post-processing the data acquired during fieldwork had also to be transformed into RINEX format which is an interchange format for raw satellite navigation systems data. This was done using Trimble ConvertToRINEX software.

An advantage of PPK is also that Ephemeris data can be used. Ephemeris data contain information about the exact location of the satellites. This allows to obtain a better result for the positions of the surveyed points since removes ephemeral errors from the solution. The Ephemeris data was downloaded from the International GNSS Service (IGS) website and was acquired in coincidence with the same days the surveys were performed.

Once the three datasets; the GCPs survey data, the Sisimiut Reference Station data and the Emphemeris correction data were obtained, they were used as input for the processing. This processing was done using Leica Geomatic Office (LGO) which provided as output the centimeter precision post-processed coordinates of the GCPs as well as other desired information like quality of the results.

2.3 DEM generation

The DEM generation step comprises the 3D model of the object and the georeferencing.

In the present paper, the data were processed using *Agisoft Photoscan.* The workflow is divided as follow:

- *3D Reconstruction* - This is the core of the SfM workflow. As explained above, the algorithm identifies and matches identical points in overlapping pictures in order to calculate relative camera positions. The result of the images alignment step is the so-called sparse point cloud. The points in the sparse cloud are the matching points in the 3D local reference system used by the software. To achieve a better coverage of the object, the sparse cloud can be further processed to obtain the dense point cloud. The point clouds need to be manually adjusted by removing noise e.g. points located far off the reconstructed surfaces. The noise is attributed to fictitious matching points, for example clouds, background or prospective deformations.

- *Georeferencing* - Once the dense cloud is obtained, the so-called mesh can be computed. Georefernciing takes place at this point and is achieved by manually selecting the GCPs, here called markers, in the pictures. Each time a new GCP is placed, the software sets it automatically in all the other overlapping pictures, according to the 3 dimensional model reconstruction. The position of the new GCP proposed by the software can be erroneous. In this case the GCP position must be corrected to be coherent in all the pictures. After the placement of the markers, the post processed coordinates have to be imported and the model is then positioned in a global reference system. The model can be eventually exported as DEM and orthopohoto.

3. RESULTS

3.1 Pictures Acquisition

The fieldwork took place during 4 days between the 11 and the 17 August 2014. On August 11 and 12 the team focused on picture acquisition, taking advantage of the good weather, which ended August 12. The morning of August 14 the team proceeded with the GCPs ground survey, which could not be completed due to low visibility. Eventually, August 17 the weather permitted to reach the top of the glacier and to complete both the pictures acquisition and the GCP survey.

The pictures were taken from 4 distinct peaks, 3 of them situated on the orographic right side of the basin. The major peak on the orographic left side of the glacier, even though being a crucial key point, was not climbed due to weather, time and safety issues. In total, after filtering blurry and wrongly exposed pictures, 622 pictures were deemed suitable for the DEM generation. The camera positions are shown in Figure 1.

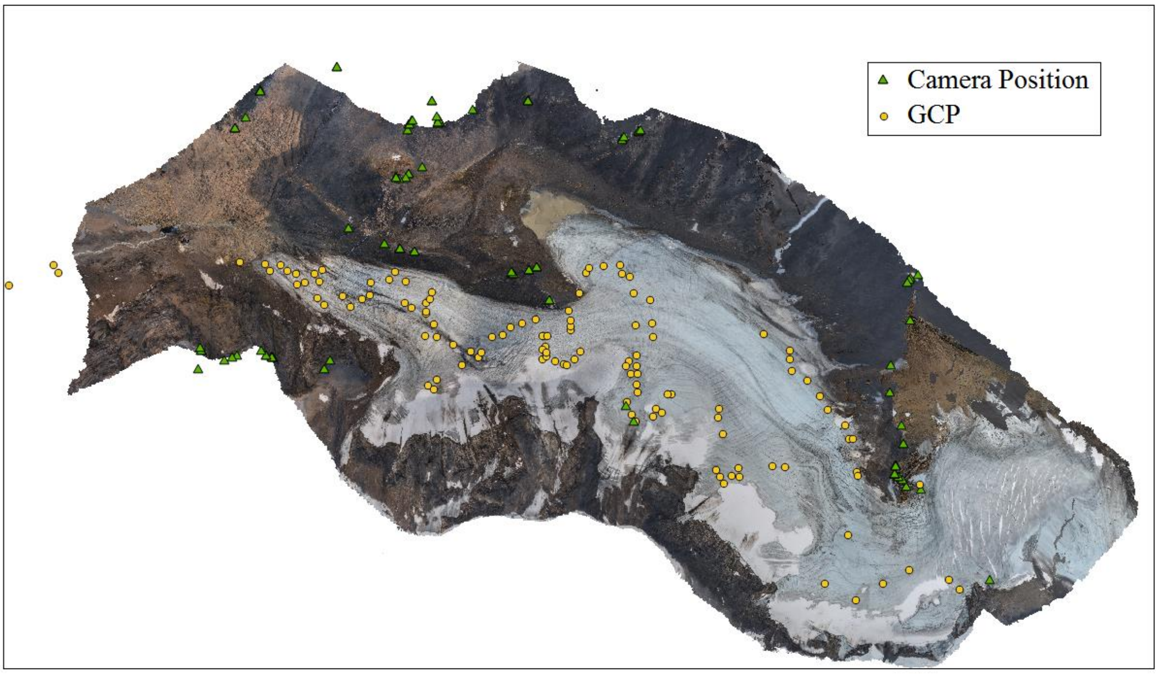

Figure 1: Camera viewpoints and GCPs positions displayed on a generated orthophoto.

3.2 GCPs Survey and Post-Processing

The GCPs were acquired taking advantage of in-situ boulders and debris, which led to a denser mapping of the tongue and the sides of the glacier (Figure 1). Eventually, 138 points were collected on the glacier surface and 8 points in the hydrological basin below. For each point, a picture of the selected GCP marker was taken in order to identify it in the pictures used to reconstruct the model.

The output of the post processing given by LGO consists on a spreadsheet table containing all the coordinates' values of the GCPs. The coordinate reference system used for this purpose is UTM Zone 22 North (WGS 84), EPSG: 32622, which uniquely identify the point's location with Northing, Easting and Ellipsoidal height. The coordinates exported from LGO in this coordinate system will be then used in Agisoft Photoscan to georeference the 3D model.

3.3 DEM Generation

Before using the pictures for the DEM construction, a basic image processing was performed to correct wrong exposures, enhance contrast and sharpen the images. A quick test using 50 pictures of the tongue demonstrated that the image processing increased the sparse cloud density by 3%.

At first, it was decided to use a single dataset, using all the pictures. However, it was noticed that the software has problems to understand complex scenes with varying data coverage, in such cases the software tends to focus and reconstruct only the best covered area. Thus, the number of pictures was reduced from 622 to 249, trying to achieve an equal distribution over the glacier perimeter, and the software managed to successfully process the scene. The sparse cloud counted 0.51 million points. However, the result needed to be processed since the surfaces were not well defined due to the high number of outliers (points not located on the main ground surface). In a first step the sparse cloud was edited by manually removing large groups of outliers. Secondly, automated filtering is applied in Agisoft based on reprojection error and image count criteria (Agisoft, 2013). After editing, the sparse cloud density was reduced to 0.25 million points. Most of the deleted points were either outliers or were located in areas of high reflectance, e.g. snow covered areas and watersheds.

The next step in the workflow is the dense cloud generation, which has to be computed on the sparse cloud obtained previously. The purpose of this step is to increase the density of points and further filtering for outliers. The software took about 24 hours to generate a dense cloud of 18.2 million points, with an average density of 1.71 point/m^2. The type of cloud generation depends on the filtering method chosen by the user. Here *aggressive filtering* was chosen, which is more suitable for representing smoother surfaces and removal of outliers. The dense cloud was then classified automatically, using the function *gradual selection*, which allows to select the points that do not belong to the surface. All outliers on the glacier were mapped and classified as noise, while the remaining part was classified as actual topography and selected for further mesh computing.

After the classification, the mesh was computed on the aforementioned actual topography. The mesh was generated choosing the height surface option in the mesh generator tool, in order to preserve the terrain properties and not to over smooth the features. As result, Agisoft produced a mesh composed by 3.3 million triangles. However, the mesh still includes some spikes on steep snow-covered areas, due to interpolation error in the holes of the dense cloud. The spikes were manually removed and the remaining holes automatically filled.

The 3D model was finally georeferenced. In total, 50 GCPs markers were identified on the pictures and used for referencing the model. Agisoft computes for each marker the error in each dimension (Northing, Easting and Elevation) and performs linear transformation of the model to minimize the total error, given by the Euclidean distance between the "real" coordinates of the point and its position in the model. The first and second order statistics and the maximum errors are presented in Figure 2. It can be seen that the discrete error distributions fit to the normal distribution, indicating that georeferencing errors are not systematic.

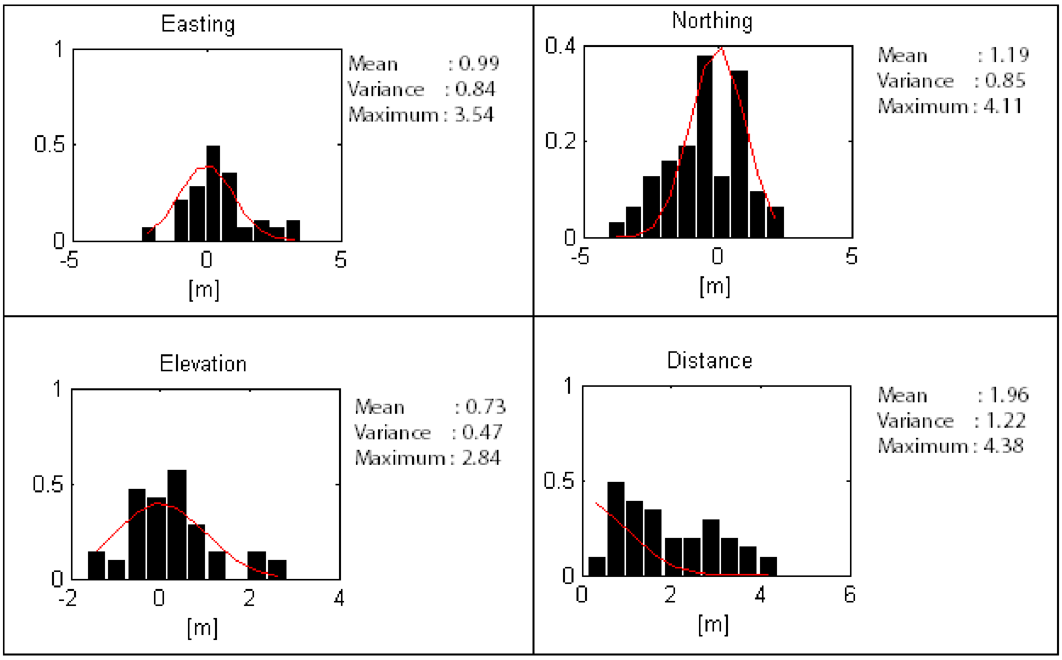

Figure 2: Georeferencing error statistical analysis.

The model was finally exported in *geotiff* format, with coordinate system UTM WGS 84, zone 22N. The pixel size is 0.79 m. The mountains in the orographic right of the basin, where the amount of matching points is very low and the reconstruction mainly belongs to dense points and gaps interpolation, the representation is poor and not reliable (Figure 3). However, the entire glacier is represented with high resolution. Also the mountain range in the orographic left of the basin appear extremely accurate. The entire workflow is illustrated in Figure 4.

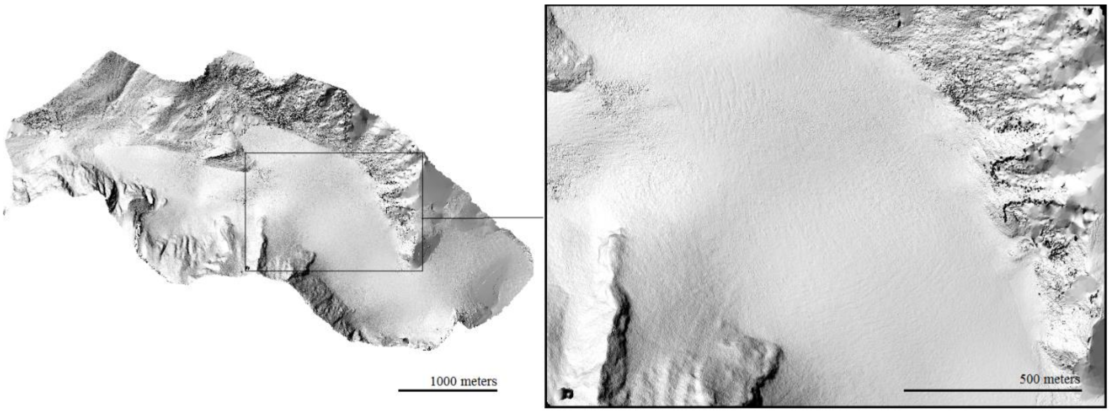

Figure 3: Hillshade of the DEM and detail visualization. Notice the difference between interpolated features on the orographic right hand side and the high resolution representation of the glacier surface.

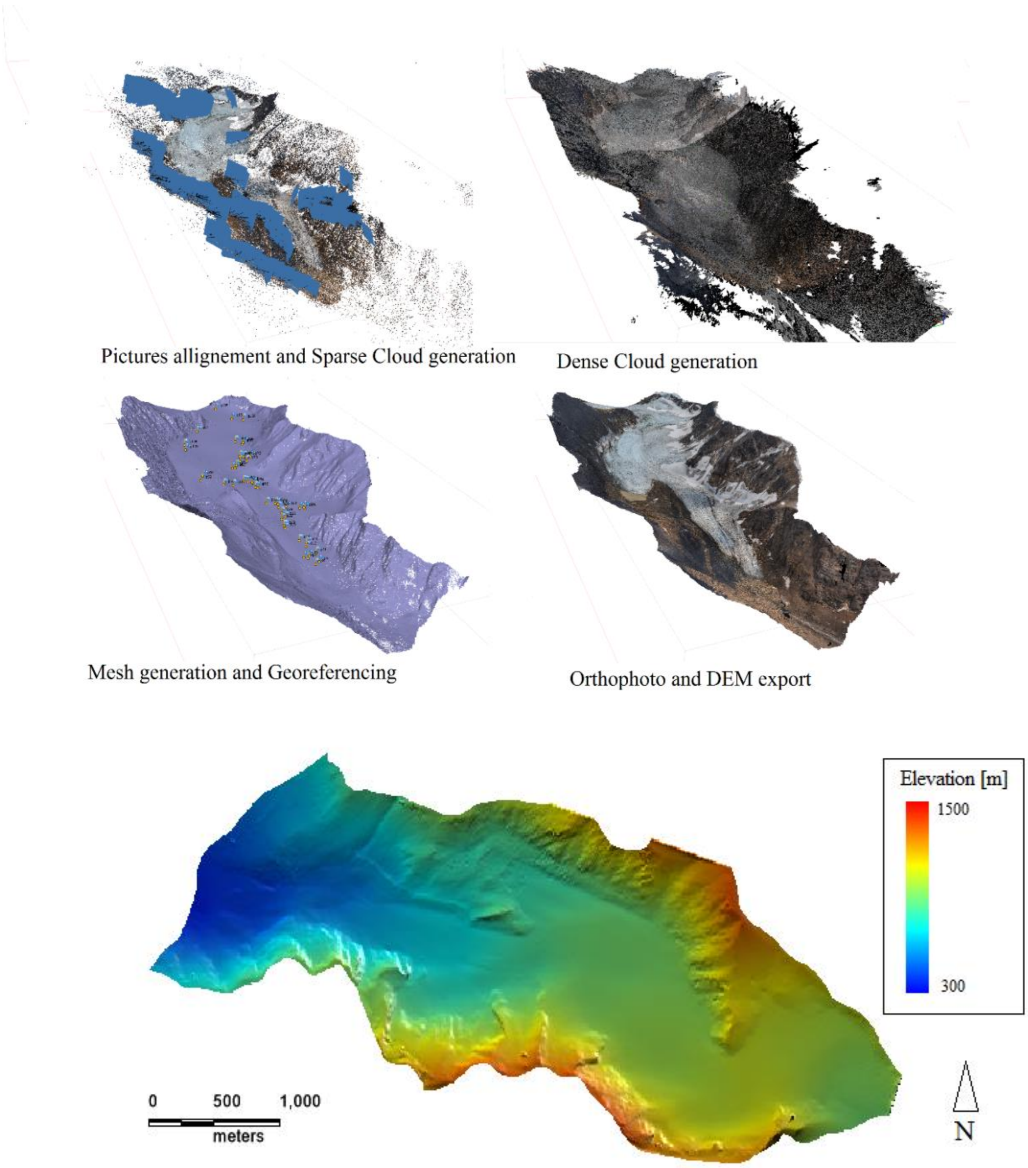

Figure 4: SfM workflow using Agisoft Photoscan and Digital Elevation.

4 DISCUSSION

4.1 Pictures acquisition

The fieldwork campaign is the decisive part of the project. A good photoset is necessary for a good coverage and a good DEM. The pictures were taken from only 4 main peaks, in the glacier surroundings. Considering the poor amount of positions, the pictures were highly redundant. In order to test if redundant pictures increased the resolution of the DEM, a specific model of the glacier tongue was built, because the latter has optimal coverage with images from a variety of viewpoints.

However, the model generated with a dataset of 106 images did not differ much from the same area represented in the model of the entire glacier, where the tongue is covered by half of the amount of images. This simple test helped to understand that numerous redundant pictures do not improve the DEM resolution significantly. It is preferable to keep the dataset as small as possible to reduce computational and rendering costs, given that the landscape is entirely represented.

Thus, the number of different viewpoints appears to be crucial to obtain a DEM of optimum quality. The area with poorest coverage is the mountain range on the orographic right hand side, which is only represented by a set of images taken along a 700 m ridge on a peak 1.5 to 2.5 km away from the target. The relative movement of the features in this dataset is minimal and this is likely the reason for the inaccurate representation of the area in the model. Hence, accessing the highest peak in the orographic left hand side would have been necessary to improve the mentioned sector.

The light conditions encountered during the fieldwork were diverse and influenced the DEM generation less than expected. The ideal light condition is diffuse light, given by high clouds covering the sun and limiting heavy shadowing. Pictures from the orographic left hand side were taken under worst conditions: morning backlight sun creating strong reflections on the ice surface. However basic image processing reduced overexposures and deep shadows and surface features were defined clearly enough for referencing the pictures.

4.2 GCPs Survey and Post-Processing

During fieldwork, 124 GCPs were acquired. However, only 50 points could be identified in the images used for SfM. The process to identify the points is challenging for two main reasons. First, features might not be as easy to locate in SfM pictures as they appear when standing nearby on the glacier surface. Second, the pictures taken on the glacier surface during the GCPs survey have a different prospective from the SfM pictures and the point localization is done considering background features. However, many GCPs were collected in low clouds and foggy conditions, making the background useless. Also, the time frame in which the field work took place was relatively long and due to intensive melt snow covered areas decreased strongly, making the identification of the points even more challenging. This was noticed in particular in the upper part of the glacier, where GCPs were acquired 4 days before the SfM pictures. It is concluded that for optimal usability the GCPs have to be measured within a time frame as short as possible.

4.3 DEM generation

Due to the low number of camera positions, the DEM generation process was more complex than expected. Agisoft performs best if the pictures are taken evenly around the feature and this was not the case. In the available literature only cases of study with optimal datasets are described. The method used to find the optimal workflow was based on trial and error.

In general, there is a tradeoff between detail and structure reconstruction. Some areas, as the tongue of the glacier, can be reconstructed with a high level of detail, thanks to the optimal image coverage. However, if the detail is maximized in this area, other areas with poorest coverage will be represented mainly with interpolated points. In order to reduce excessive interpolation, the structure reconstruction was prioritized in each step of the workflow:

- *Model Setup* - As explained above, a reduced dataset with a similar number of pictures for each camera position is suitable to reconstruct the scene, rather than simply selecting all the pictures.

- *Sparse Cloud* - The optimal DEM was obtained by filtering out 50% of the points of the sparse cloud. This means that half of the matches generated by the dataset is basically noise. Looking in detail through the matching points it was noticed that the noise is mostly caused by shadows, underexposed rocky areas, irrelevant background and clouds. Thus, a test was performed where all the sources of noise were masked out in order to try to generate a "cleaner" sparse cloud. It was found that these features, background in particular, are used by the software to estimate the scene structure. The test revealed that Agisoft could not reconstruct the scene with masked pictures. It could be still useful to mask only the sky in the pictures. However, the masking has to be done manually which is very time consuming. Thus, the automatic filtering of the sparse cloud was preferred rather than masking sources of noise.

- *Dense Cloud* - The optimal dense cloud was generated by using the options "*medium precision*" and "*aggressive filtering*" in Agisoft. The density of 1.71 points/m^2 in the final dense cloud is large enough for the aim of the project and allows for quick and efficient data handling.

- *Mesh* - The mesh was generated at the highest resolution option available in Agisoft, poorest resolutions resulted in an excessive loss of details. There are some areas in the right hand side mountain range where interpolation artifacts are predominant. In such areas the mesh is either too smooth or too noisy (Figure 4). This is believed to be a direct consequence of the poor picture coverage of the area. Thus, this lack of detail in the mesh could not be solved in the processing stage, since the problem is related to insufficient image coverage.

- *Georeferencing* - The Georeferencing elevation error (0.73 m) is a satisfying result. The elevation accuracy is more relevant than the global accuracy because the use that will be done of this DEM is for the geodetic mass balance of the glacier, which is based on elevation differences. Thus, a sub-meter elevation accuracy meets and fulfills the aim of the project. However, it is interesting to discuss the sources of error. Theoretically, a model without structural distortions and precise georeferencing should have an accuracy of the same order of magnitude of the GPS coordinates precision of the GCPs. In this case the global error (1.96 m) is one order of magnitude higher than the GPS precision. Identifying the source of the error is challenging but some possible reasons are listed as follow. First, the GCPs in general are taken on the edge of stones measuring up to several meters. It is actually complicated to identify the exact point on the stones where the coordinates were taken since in certain pictures the GCP has to be identified within only few pixels. Second, taking the GCPs on the edge of the stones means that for certain camera positions the actual position of the GCP is hidden. Selecting the precise position of the GCP in this situations is not possible, since the exact position does not appear on the picture. Third, it was noticed that the debris on the glacier moved during the field work. These movements are due to high melting rates, estimated to be approximately 30 cm over the field work period, induced by strong winds. The vertical melt is translated into horizontal shifts by tipping over. Finally, the errors are also due to structural deformation of the model, which are impossible to correct at the current state of art due to the lack of an algorithm capable to set non-linear transformations to the reconstructed object.

4.4 Future recommendation

Using SfM a high resolution DEM of known precision could be generated. The results can be improved mainly in the fieldwork step. A time window of 6 days is too large to guarantee stable conditions of the glacier surface, and the error is expected to grow with the time between picture acquisition and GCPs survey. The survey should take place in consecutive days. Considering the actual amount of time used for the survey, it is evaluated that the entire fieldwork can be carried out in two days. It is also suggested to take advantage of two additional team members and divide the group in two. One team should be in charge of the GCPs survey. At the same time, the second group should take the pictures for the SfM from the viewpoints. In this way there is no time lapse between picture acquisition and GCPs surveys. Moreover, the GCPs identification in the pictures for the SfM would be more efficient, since the GCPs team would appear in those pictures while acquiring the points.

5 CONCLUSION

The present paper shows the process of generating a DEM of the Aqqutikitsoq glacier using ground based Structure from Motion. The workflow is described and discussed step-by-step from the fieldwork stage. The difficulties faced during the fieldwork did not allow to achieve an optimal photoset and part of the right mountain range of the basin is not well represented due to poor picture coverage. However, the left mountain range and, most important, the entire glacier, are represented at high resolution (0.79 m) and high vertical accuracy (0.73 m). The reliable points outside the glacier will be used as a reference to evaluate pre-existing DEMs of the area, making possible to estimate the geodetic mass balance. The level of detail achieved on the ice and snow covered areas was not affected by optical reflectance issues. Using traditional methods of DEM generation, such as LiDAR, a comparable level of resolution and accuracy could have been only achieved at high costs, considering the remoteness of the area. It is concluded that all the aims of the project are fulfilled.

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