Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Civil and Environmental Engineering

Erik Kleiven Rynning

Snow measurements with drones

Master's thesis in Hydropower Development
Supervisor: Oddbjørn Bruland
June 2019

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Sira-Kvina
KRAFTSELSKAP

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Preface

This is a thesis in the subject TVM4915 Hydropower Development, Master's Thesis (2019 VÅR) and is the final paper for this study. The thesis is submitted to the Norwegian University of Science and Technology (NTNU).

This thesis about snow measurements with drones was provided by Kaspar Vereide in Sira-Kvina Power Company. Sira-Kvina Power Company is located at Tonstad village in Vest-Agder County. Sira-Kvina has a total installed capacity of 1760 MW from 7 hydropower plants and is the owner of Tonstad hydropower plant, which is Norway's biggest hydropower plant by production. Tonstad hydropower plant produces 3800 GWh per year, which is more than half of Sira-Kvina's total power production.

Several people have contributed to this thesis and deserve a big thank you:

- My supervisor Oddbjørn Bruland for giving advice and lending equipment.
- My co-supervisor Kaspar Vereide in Sira-Kvina Power Company for providing the thesis, joining me during summer survey, giving inputs and advice.
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- The people at Verkstedloftet for all the fun and nice moments during the thesis period.
- To Hydropower Development 2017-2019 for two amazing years, I would never have been without it.
- Johannes Mendgen in Pix4D SA for providing me with a free license to Pix4Dmapper during my thesis period.
- My girlfriend Majken Førnes Johansen for her patience and support.
- To my family for always supporting my choices

Summary

Snow measurement with drones by use of photogrammetry to create 3D models of an area is a new technology that can be very useful for hydropower companies to estimate snow storage. With that, the hydropower companies can find the expected runoff from the snow storage into the reservoirs. An improved estimation of expected runoff from snow storage will give better foundation to plan the operation of the reservoir and increase the income from production. Snow volume was requested to be measured at three different sites in Sira-Kvina Power Company's catchment area. The three chosen sites were Flatstøl, Tjørhom and Nesjen which is located in different areas of the catchment area. At these sites, photogrammetry with drone were performed with and without snow on the ground. 3D models from photogrammetry was made in the Pix4Dmapper software and volume calculations were performed in the software CloudCompare. Several test flight were performed in different weather conditions to validate which conditions were working or not, before flights in wintertime to take photogrammetry of the snow. The results from the test flights revealed that only conditions with sun from clear sky was appropriate due to much light reflection from the snow in overcast weather. From the winter flight at Tjørhom, the GPS in the drone was not correctly calibrated and the obtained 3D model was not usable. At Nesjen, 3D models from bare ground and snow covered ground was twisted according to each other and not usable for volume calculation. The 3D model at Flatstøl was without issues except from a small offset between the two models in x and y direction. From Flatstøl, a mean snow depth obtained from photogrammetry was 0.48 meters and from manual measurement, a snow depth of 0.35 meter was found. An increase in snow volume of 38% was found from the 3D models according to the manual measurements. According to this, the results showed that with a larger area covered by the drone, more differences in snow accumulation is obtained than with manual measurements. The increased calculated snow volume gives possibility for better planning of operation of reservoirs since the calculated runoff would be higher. By assuming that the calculated increased expected runoff is valid for half of Sira-Kvina Power Company's catchment area, an increase in calculated runoff of 59.67 million m^3 of water is found. By producing more power in high demand periods, an extra income of 1.496 million NOK is expected.

Samandrag

Snømåling med drone ved bruk av fotogrammetri for å lage 3D modellar av eit område er ein ny teknologi som kan vere veldig nyttig for vasskraftselskap for å berekne snømagasin. Med det kan vasskraftselskapa finne forventa avrenning frå snømagasinet til vassmagasina. Eit forbetra anslag for forventa avrenning frå snømagasinet vil gje eit betre grunnlag for å planlegge bruk av vassmagasinet og auke inntekt frå produksjon. Snøvolum var førespurt til å bli funnen på tre forskjellege plassar i Sira-Kvina kraftselskap sitt nedbørsfelt. Dei tre valde plassane var Flatstøl, Tjørhom og Nesjen som er lokalisert i ulike områder av nedbørsfeltet. Ved desse stadane var det utført fotogrammetri ved hjelp av drone med og utan snø på bakken. 3D modellar frå fotogrammetrien var laga i programmet Pix4Dmapper og volumkalkuleringar vart utført i programmet CloudCompare. Før flygning med fotogrammetri på vinterstid vart fleire prøveflygningar utført i forskjellege vêrforhold for å validere kva slags vêrforhold som fungerte og ikkje. Resultatet frå desse prøveflygningane slo fast at det var kun vêrforhold med sol frå klar himmel som var tilstrekkeleg på grunn av for mykje lysrefleksjon i overskya vêr. Frå vinterflygningane ved Tjørhom var ikkje GPS-en i drona korrekt kalibrert og 3D modellen som vart laga var dermed ubrukeleg. Frå 3D modellane ved Nesjen var modellen frå bar grunn og snødekt grunn skeive i forhold til kvarandre, noko som gjorde dei ubrukelege for volumkalkulering. 3D modellane frå Flatstøl var utan problem utanom ein liten forskyving i x og y retning mellom modellane. Frå Flatstøl vart det funne ei gjennomsnittleg snødjupn på 0,48 meter frå fotogrammetri og ei snødjupn på 0,35 meter frå manuelle målingar. Det vart funne ein auke i snøvolum på 38% i 3D modellane i forhold til manuelle målingar. Resultata viser at med eit større areal dekt ved hjelp av ei drone så finn ein meir forskjellar i snødjupne enn ved manuelle målingar. Det auka kalkulerte snøvolumet gjev moglegheiter for betre planlegging av bruk av vassmagasin sidan den kalkulerte mengda avrenning er høgare. Ved å anta at kalkulert auka avrenning er gyldig for halve nedbørsfeltet til Sira-Kvina kraftselskap, så er det funne ei auka avrenning på 59,67 millionar m^3. Ved å produsere meir kraft i periodar med høg etterspørsel av straum, er ei ekstra inntekt på 1,496 millionar kroner forventa.

Table of contents

List of figures

List of tables

Abbreviations

DSM – Digital Surface Models

EGM – Earth Gravitational Model

GCP – Ground Control Points

GPS – Global Positioning System

GSD – Ground Sample Distance

GWh – Gigawatt hour

KWh – Kilowatt hour

m.a.s.l – Meter above sea level

MW – Megawatt

MWh – Megawatt hour

ND – Neutral Density

NIR – Near Infrared

NTNU – Norwegian University of Science and Technology

NVE – The Norwegian Water Resources and Energy Directorate

PL – Polarized Lens

SWE – Snow Water Equivalent

UAS – Unmanned Aerial Systems

WGS – World Geodetic System

1 Introduction

In Norway 1/3 of the precipitation comes as snow. The snow accumulate during wintertime and works as a water storage until it melts. It is crucial to know how much runoff the snowmelt will cause, because this has several important factors: Power companies must know how much water they have available for production, the government can calculate flood risk and by that know if there is possibility for damage on infrastructure. Using snow storage data can also be used to take environmental consideration. (Norges vassdrags- og energidirektorat, 2016) The Norwegian Water Resources and Energy Directorate (NVE) mounted the first snow pillow in Norway for measuring Snow Water Equivalent (SWE) on Filefjell in 1967. A snow pillow detects the weight of the snow on top of the pillow by how much it is compressed. SWE is a number telling how much water that is in the stored in the snow, and is found by

$$SWE = \frac{\rho_s}{\rho_w} * HS \tag{1}$$

Where ρ_s is the snow density (g cm^{-3}), ρ_w is the water density (1 g cm^{-3}) and HS is the snow depth in cm.

Today there is around 20 snow measurement stations for SWE in Norway spread around the country and measure SWE from 85 m.a.s.l. to 1400 m.a.s.l. The most normal instrument to measure SWE is a snow pillow, but snowweights and gammasensors are also used. (Norges vassdrags- og energidirektorat, 2017)

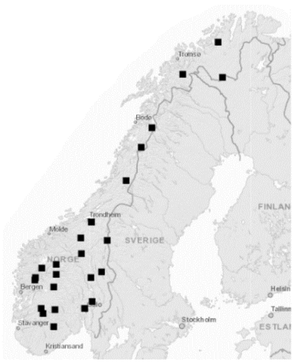

Figure 1: NVE's measurement stations for SWE in Norway. (NVE, et al., 2019)

Power companies like Sira-Kvina power company measure the snow depth and the SWE manually to get an idea of how much runoff they can expect to their reservoirs from the snow storage. The measurements are done at fixed spots, at specific times every year. Sira-Kvina Power Company do their snow measurement in January/February and in March/April and send in the results so NVE get a general overview and input to the climate analysis. The snow measurement demand manpower and have costs with transportation of workers. Sira-Kvina Power Company uses snowmobiles for traveling to the different locations where they do measurements. By using drones the snow measurement will be done over a larger area and can possibly be more accurate than measuring the snow depth at certain locations. The purpose of this thesis is to test and get knowledge on how accurate snow measurement with drone is and if it is a reliable source that can be used in the future.

2 Theory

Measurement of snow depth using photogrammetry from Unmanned Aerial Systems (UAS) like drones is a generally new topic but have been performed in some previous cases. Monitoring snow using UAS can be useful for snow hydrology, calculating runoff to reservoirs for hydropower and mitigation, and it can be used to find snow depth in areas where snow avalanches can occur (Bühler, et al., 2016). Specific snow depth in some regions can give important information to different types of users.

In some places, snow depth is calculated by reciving information from nearby weather stations or interpolating results from manual measurements. These results can be inaccurate in alpine regions where the wind is highly affecting the snow distribution. The SWE can be found either by for example snow pillow, cosmic ray or manual measurements. Compared to using laser scanning from either manned or unmanned aircrafts to find snow depth, photogrammetry with UAS is a cheaper option when cost of equipment and staff is taken into consideration.

In this section, two different projects where UAS have been used will be examined. Obtaining snow depth by using drone can be favourable for hydrologists and hydropower plants if the obtained snow depth and expected runoff is accurate.

2.1 Location 1: Close to Belverdere glacier, Italy.

The study site is at 2070 m.a.s.l. and at the study site the vegetation contains rocks and grass. There are no trees in the approximated 6700 m^2 large study area, but two streams are crossing the area. The terrain is homogeneous with a maximum terrain variation of approximately 7 meters.

The snow depth was found by comparing two Digital Surface Models (DSM) where one was obtained in summer with bare ground and the other at peak accumulation of snow. They were able to make DSM's by taking pictures with a hexacopter. Flightheight in summer was on average 65 meters and 60 meters in the winter. That gave a Ground Sample Distance (GSD) of 0.02 m. GSD is a number on how many centimetres of the ground that is covered in one pixel.

A front overlap of the images was set to be 80% and 60% for the side overlap. Since snow can be quite similar a higher overlap between the images can be applied to increase the chance for the program to recognize similar pixels. In this project 84 images was used in the summer model and 144 pictures in the winter model. In the summer the flight was performed at around 10 AM and around noon in winter time. If the camera on the UAS has high resolution and the surface area with snow is homogeneous, it can cause problems to recognize pixels between the pictures. (Avanzi, et al., 2018)

GCP (Ground Control Points) was used to increase the accuracy of the geolocation. GCP's are placed out in the survey area as large squares, often black and white, to easily spot them from the photogrammetry. The GPS position is manually measured at each GCP point and is added to the software for processing the pictures. The program used for processing the pictures into a 3D model in this project was Agisoft Photoscan.

According to manual probing in the area the snow height found between the two 3D models was larger than the snow height found from manual probing in 89% of the area. The remaining 11% was either no difference or showed less snow than manual probing. (Avanzi, et al., 2017) The reason for these differences can be either that the snow height is underestimated from manual probing or an overestimation in Agisoft Photoscan. Different topographical features can cause differences in snow height measurement between the model and manual probing. (Avanzi, et al., 2018) The bare ground can have different coverage in summer and winter. During summer survey the length of the grass will be larger than in the winter survey, which will affect the snow measurement in Agisoft Photoscan.

2.2 Location 2: Tschuggen and Brämabühl located close to Davos, Switzerland

Tschuggen is located at 1900 m.a.s.l in a valley that is in good shelter from strong winds and Brämabühl is located at around 2500 m.a.s.l. at a peak loacation where wind is affecting the snow distribution. In alpine terrain where it is hard to enter a project site by foot or skis to do snow measurements, UAS is advantageous due to easy portability and it can take off and land relatively far away from the site of interest in good weather conditions.

As in the project close to the Belverdere glacier in Italy, Agisoft Photoscan was used in this project. The results from the snow measurement with the UAS reveal that the snow height is found to be 0.11 meters lower than the manual probe measurements on average. The partly high grass and small bushes that was on Brämabühl at the surveyday without snow can probably explain the reason to this difference. The flight without snow was performed on 21st September 2015. In Tschuggen there was different types of vegetation that could be up to 0.50 meters high in the summer survey. When snow starts to accumaulate, the vegetation will be pressed down due to the weight of the snow and form a layer on the ground that is basically snow free. When mapping with photogrammetry in summer and winter, processing the pictures to DSM's, and comparing the models will underestimate the snow depth since the summer DSM is higher with the vegetation. To get more accurate measurements photogrammetry in summer should be done just after mowing, if the project site will be mowed during the year. Alternatively, right after snowmelt in the spring if the site is hard to reach. When measuring the snow depth with manual measurements, the probe will penetrate the vegetation that is pressed down and give an overestimation of snowdepth. In these cases the real snowdepth should be somewhere between the manual results and the result from the DSM's. (Bühler, et al., 2016)

In the projected DSM it was found that places with shadow cause noise in the model that can lead to wrong snow height calculations. Shadows could peak up to 0.40 meters above the rest of the snow surface in the model. In bright conditions, noise was also obtained and at 0.15 meters at maximum above the original snow surface.

A testflight in wintertime was performed on an overcast day with fresh snow on the ground at Tschuggen. In those conditions, the ground looks very homogenous and it is expected to be the worst conditions for photogrammetry. Different Near Infrared (NIR) filters was tested and the test showed that using a NIR830 (absorbing wavelengths larger than 830 nm) gave the best results for the DSM. (Bühler, et al., 2016)

2.3 Study in Canada

From a study in Canada when measuring a snowpack that is less than 1 meter in depth with UAS, the precision of the model was ranging from -5.7 cm to 10.3 cm. (Fernandes, et al., 2018) That either means that the total volume of the snowpack from the model can vary negatively or positive according to the manual measurement. Higher height during flight gives more uncertainty. For a site with plain snowcover and a size of 100x100 meters, a 5 cm difference between the actual snow cover and the model gives a difference of 500 m^3 with snow, which is a lot over such a small area according to large catchment areas.

In the study GCP's were used and the accuracy of the model was better than reported from other studies. Fernandes believe that is a result of a high visibility of GCP's in the images obtained from the drone. (Fernandes, et al., 2018) At maximum, a GCP point was visible in 30 images.

3 Metodology

3.1 Study sites

The study sites are in Vest-Agder County in Norway, close to the village Tonstad where Sira-Kvina Power Company have their main office. The sites are on places where Sira-Kvina normally do their snow measurements. That makes it easier to compare results that is done with the drone and the manual measurements. In total three different sites were chosen. The sites were Flatstøl, Tjørhom and Nesjen. All sites are northeast of Tonstad village.

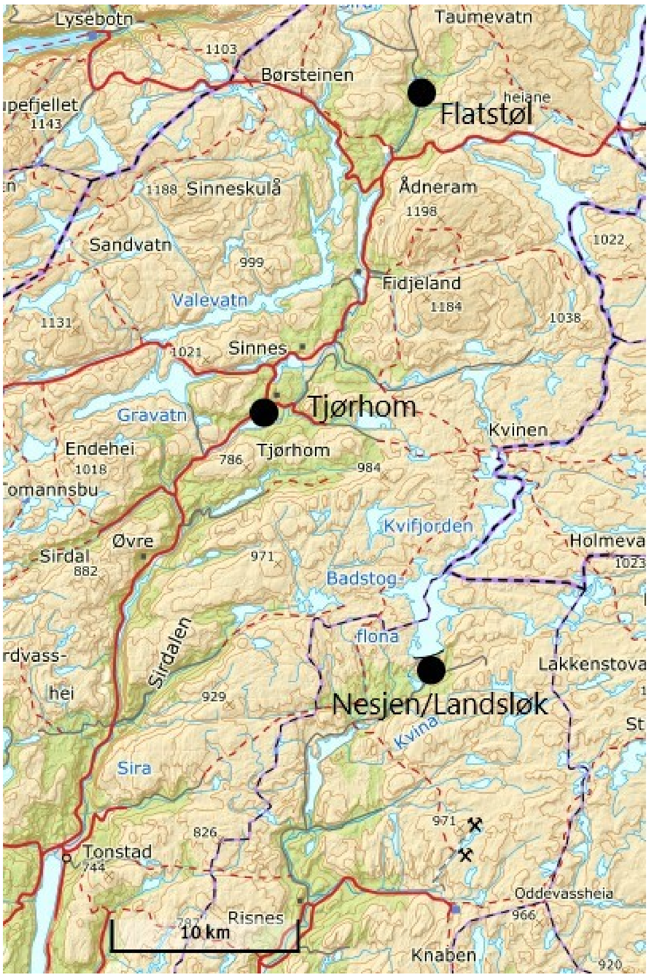

Figure 2: Survey sites (Kartverket, 2019)

3.1.1 Flatstøl

Flatstøl (59°03'05.9"N 6°57'14.3"E) is a quite plane site with minor elevation differences located at 630 m.a.s.l. At this site the vegetation consist mostly of grass and small bushes. There are marshes, a couple of trees and a river stream passing through the site. On the right side of the road, there is a small rocky knoll and a cabin.

Figure 3: Survey area at Flatstøl

3.1.2 Tjørhom

Tjørhom (58°53'11.8"N 6°51'00.3"E) is as Flatstøl a quite plane site with minor elevation differences located at 500 m.a.s.l. The study site is consists mostly of farmland. There are a few trees, some fences to separate fields and on the left side of the road there is a small rocky knoll.

Figure 4: Survey area at Tjørhom

3.1.3 Nesjen

Nesjen (58°46'35.6"N 7°01'41.7"E) is located at 700 m.a.s.l. This site consist of varying elevation with an elevation difference of over 50 meters. The area consist of bare mountain with vegetation in between. At the lowest point the area consist of grass. The site also consist of trees and a small quarry at the site.

Figure 5: Survey area at Nesjen

3.2 Type of drones and applications

Two different drones has been used during this project. Sira-Kvina Power Company provided a DJI Phantom 4 for taking pictures for the 3D models. A DJI Mavic 2 Pro was provided by NTNU for test flights in different weather conditions and as a backup drone for taking pictures for the 3D models. Both drones used a mobile phone or an iPad to connect to the controller to set parameters and perform missions. The screen on the iPad/mobile phone was also used to connect to the camera on the drone to be able to get a view from the position of the drone.

Mainly three applications have been used: DJI GO 4, Ctrl+DJI and Pix4Dcapture. DJI GO 4 is used for free flight mode, e.g. when taking pictures manually in different weather conditions. The amount of pictures needed during testing to know if it is possible to make a working 3D model is not so high, and therefore it is faster to take pictures manually instead of plotting in a path for the drone to follow. Ctrl+DJI is an application that show information like position, velocity in x, y and z direction, battery percentage, yaw, pitch and roll for the drone that is connected. Yaw, pitch and roll tells us about the drone's movement according to its axis.

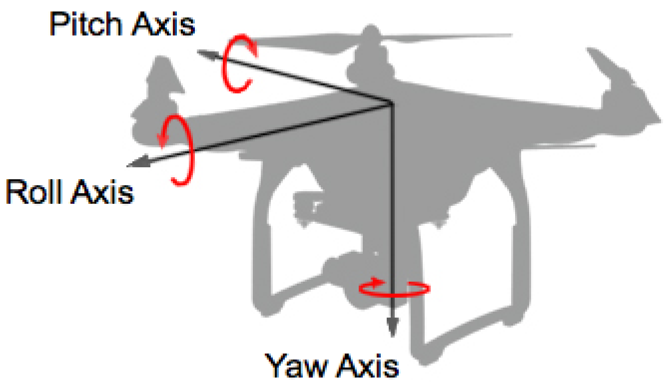

Figure 6: Direction of pitch, roll and yaw axis (DJI, 2016)

Ctrl+DJI is needed to use Pix4Dcapture on mobile devices and it is possible to open Pix4Dcapture from Ctrl+DJI. These apps are developed from Pix4D and fulfils each other. Pix4D have developed the software Pix4Dmapper that will be used to create the 3D models. (Pix4D SA, 2019) In the Pix4Dcapture application there is the option to do different missions and give settings to the missions. The main missions to use for making a 3D model is Double Grid mission and Circular mission.

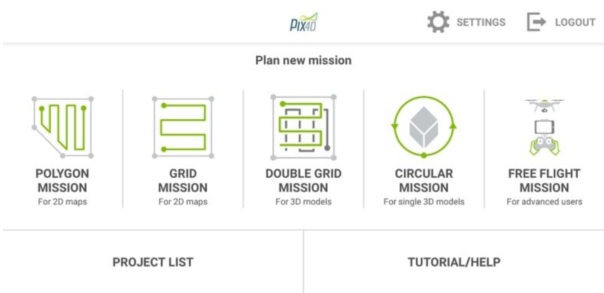

Figure 7: Screenshot from the menu in the Pix4Dcapture app

Depending on the mission, different parameters are needed to be set for the selected mission. Parameters can be mission area, flight altitude, speed, camera angle, image overlap and angle between each picture. The different settings will have an impact on GSD and the flight time for the mission.

3.3 Geolocation of drone

The drones that are used for this project have a Global Positioning System (GPS) and a barometric sensor built in the drone. For each picture that is taken, the drone gives information about the position and its altitude, this is saved together with the picture. This geolocation is important for the algorithm in the Pix4D software. When the GPS position is known the processing time of the models will be faster since the algorithm now knows which pictures that possibly have some similar pixels. (Skille, 2018)

3.4 Geoid and Ellipsoide of the earth

A geoid is a measurement for mean sea level around the earth and define where the elevation is zero. Since the world contains of land and not just sea, the mean sea level that would have been where there is land, is affected by the land. The density in the earth is different all over and that affects the geoid. Land is in general more dense than water and it also has gravitational attraction that attracts water. In general, the mean sea level is higher where there is land than on the ocean surface. (GIS Geography, 2019) In Pix4Dmapper the used Geoid in this thesis is EGM (Earth Gravitational Model) 96. The WGS (World Geodetic System) WGS84 is a reference ellipsoid to the earth and is used as a reference coordinate system for the earth. WGS84 is referred to EGM 96 so GPS systems can find accurate elevation above sea level all around the earth. (GIS Geography, 2018) The models are made in the same coordinate system to have the same reference point.

3.5 Summer flight

The summer flight was performed on 1st October 2018 on Tjørhom and Flatstøl. The flight at Nesjen was performed during the summer the same year. Flight information from Nesjen has not been accessed and is therefore not to be found in this thesis. All known information from Nesjen is obtained from the quality report generated from the Pix4D software. 237 pictures was taken at Nesjen. All flights in both summer and winter were flown with the camera angle at 70°, which means that the total area covered is larger than the area that was flown. The result from that is that a larger model of the terrain will be obtained.

3.5.1 Flatstøl

At Flatstøl three flights were performed in overcast weather at 6°C. At Flatstøl some technical issues occurred. The iPad that was connected to the controller for planning the flight missions suddenly switched off during one of the flights. The most probable reason for this is due to low temperatures combined with cold wind. However when the iPad was restarted it was easy to continue the ongoing mission. When the iPad was switched off the drone started to hover in the air in the same position until it got the command to continue it's mission. In one of the missions, the drone battery got down to 18%, and then the drone returned automatically. Also in this case it was easy to resume the mission after the battery in the drone was changed. In total 236 pictures was taken that would be used in the 3D model.

Table 1: Flight information from Flatstøl in summer survey

	Flight pattern	Altitude [m]	Area [m]	Camera angle	Front overlap	Side overlap
1. flight	Double grid	50	100x100	70°	70 %	60%
2. flight	Double grid	50	200x200	70°	70%	60%
3. flight	Circular	50	100x100	70°	10 degrees between each picture	

3.5.2 Tjørhom

At Tjørhom, three flights were performed. The flight was performed in sunny weather at 6°C. All flights were performed successfully without any issues and in total 161 pictures were taken at this site.

Table 2: Flight information from Tjørhom in summer survey

	Flight pattern	Altitude [m]	Area [m]	Camera angle	Front overlap	Side overlap
1. flight	Double grid	50	100x100	70°	70 %	60%
2. flight	Circular	50	100x100	70°	10 degrees between each picture	
3. flight	Double grid	35	100x100	70°	70%	60%

3.6 Test flight in different weather conditions

In order to get knowledge about photogrammetry on snow several test where performed. The tests included different ISO settings to vary the amount of light that was able to enter the camera lens and testing in different light due to weather conditions. The tests were performed over several days to be able to test in many different weather and snow conditions. Similar for all tests to get a good comparison was that all flights were performed with a flight height of 50 meters and a camera angle at 70°. Information as date, time, temperature and weather conditions for the test flights is found in Table 3.

Table 3: Winter test flight information

Date	Time	Temperature	Weather condition
6.2.2019	4 PM	-8°C	Fully overcast
7.2.2019	11 AM	0°C	Overcasted where the sun break through the sky
7.2.2019	2 PM	1°C	Sun from clear sky
8.2.2019	12 AM	-1°C	Fully overcast with light snowfall
9.2.2019	1 PM	2°C	Overcasted where the sun break through the sky
15.2.2019	3 PM	4°C	Sun from clear sky
17.2.2019	2 PM	2°C	Fully overcast

The first flight that was performed on the 6th February was in fully overcast weather. When humans look on the snow in overcast weather it is hard to see the contours of the landscape that is covered by snow. That is due to the snow is reflecting light in every direction that makes the landscape look similar where there is no larger differences in terrain formation. Just like the human eyes, the camera on the drone is also picking up all the light reflections and like the human eye, it is hard to see contours on the snow surface. After uploading the pictures into the Pix4Dmapper software and creating a 3D model, it was only objects without snow or snow piles that was created in the model. How Pix4Dmapper are creating 3D models is more explained in chapter *3.8 Creating 3D models in Pix4Dmapper*. Flat snow surfaces had too similar pixels so the software was not able to recognize similar pixels since everything was looking the same. On the 7th of February, two flights were performed at different times and weather conditions. In the morning it was overcast, but the sun was breaking through the skies. The result from that flight showed that it was easier to see details in the snow but not enough to make a 3D model that was able to recognize pixels. Later the same day the clouds disappeared and the sun was shining from clear sky. A new flight was performed, the pictures was uploaded to the Pix4D software and a 3D model was successfully made. The sun made the snow more clear with less reflections and it was easy to see the contours on the snow even on a flat surface. Close to the test site there were trees that gave shadow into the test site and these shadows made disturbance in the 3D model in form of spikes. The spots without shadow look perfectly fine and is flat without disturbing spikes. The software clearly had issues handling the shadows and thought it was something rising up from the ground. In a volume calculation, the shadows is a source of error if they are in the area where the volume is calculated.

Figure 8: 3D model with smooth surface without peaks

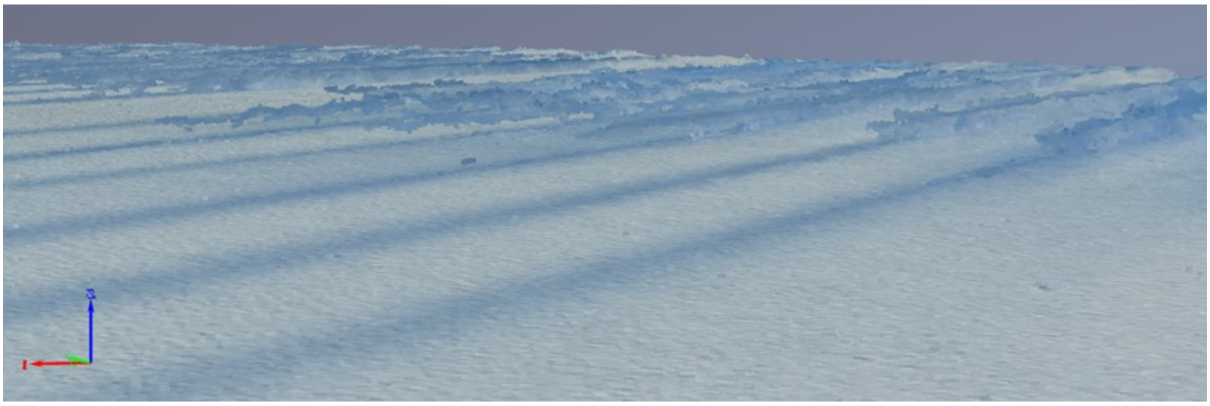

Figure 9: Error in 3D model due to peaks from shadow

On the 8th and 9th of February the weather conditions were overcast. On the 8th of February there was light snowfall as well. The expectations for performing photogrammetry in snowy weather and on a fresh snow surface on the 9th of February with flat light was low. The result also showed that it was not able to create a 3D model due to the issue with recognizing pixels. Between 9th of February and 15th of February, there was a lot of rain that changed the snow condition. Voll measurement station that is located in Trondheim, measured 30.1 mm with precipitation from the 9th of February until 15th of February, with a maximum temperature of

10.3°C which results in heavy snowmelt. (Norwegian Meteorological Institute and Norwegian Broadcasting Corporation, 2019)

When the test flights could be started again on the 15th of February, the afternoon sun was shining from clear sky. The snow on the test site was compacted by the rain in the previous days. Some places was more compact than others and it was easy to see the snow surface clearly due to the small bumps. The Pix4D software did not have any problems creating a good-looking model of the snow surface. Since the snow surface had new conditions after the rain, it might be possible to create a 3D model in overcast weather. To see if the small unevenness in the snowpack was sufficient to make a 3D model in flat light, a flight in overcast weather was to be performed as fast as possible. If it was successful, it would be an added opportunity to perform a flight with weather condition without sun on rough snow. A new test flight was performed on the 17th of February, but the wanted scenario was not obtained since the snow melted too much the last days. The snow surface was thin and started to be slushy in some areas. That was the last flight that was performed in February due to lack of snow. The result from the test flights were clearly that sun was needed to be able to create a 3D model with the Pix4D software. The sun gives less reflections from the snowpack since the light is coming from one direction and not from many directions like when it is overcast. By that it is easier to recognize pixels in different pictures since the light is coming from one direction and the snow is not looking similar over the entire area. To avoid the reflections when it is overcast, polarization filters is a possible opportunity.

3.6.1 Trial with different ISO setting

The ISO is a setting to set how much light the sensors on the camera will capture. Low ISO means less light obtained. Pictures with a high ISO will give noise, while a low ISO gives more clear images. This was clearly seen when taking pictures with different ISO settings. The ISO settings tested in this thesis ranged from ISO 100 until ISO 3600. Since snow is bright and reflects much light, a low ISO is preferred. The test that was performed also showed that on places where the snow accumulation was a bit uneven due to wind, some parts disappeared or was not captured when the ISO was increased. In general test flights was done with ISO 100 since the ISO was set to automatic. On the 9th of February a flight was performed with ISO 200. It was overcast weather where the sun breached through the skies. It was also a fresh snow cover due to the snow that came the day before. The result from the flight was that it was able to make a model, without peaks. After the rain event a new test with ISO 200 was performed on the 17th of February. When the pictures were uploaded to the Pix4D software it was not able to calibrate the images. No errors were obtained during the flight or the setup to make the model, and the geolocation of the images was fine. After the suggested troubleshooting from Pix4D, no faults were found and the reason for why it was not able to calibrate the cameras is unclear.

3.6.2 Polarization testing

Polarization filters reduce the amount of light and reflections that enter the lens and by that it filters out much of unwanted reflected light to enter the camera lens that occur on an overcast day. Due to the test results in conditions with flat light, testing with different filters is an interesting alternative to check if it is possible to obtain pictures that the program can use to make a 3D model. In total 3 different types of polarization filters were tested. These were ND4/PL, ND8/PL and ND16/PL. ND stands for Neutral Density and PL stands for Polarized Lens. The ND/PL filters could be used either as a ND filter or as a ND + PL filter. ND filters is a sunglass for the camera lens while PL as explained above can block reflected light from entering the lens. The numbers on each filter tells how much light that is reduced from entering the lense. A ND4 filter means that ¼ (25%) of the light is able to enter the lens, a ND8 let 1/8 (12.5%) of the light enter the lens and so on. The filters are also reducing the f-stop setting. F-stop is how much opening there is in the camera lens itself and when you add a filter that enables less light to enter the lens, the filter affects the f-stop. (Chris Bray Photography, 2017)

Due to delivery time and bad weather conditions, including precipitation and wind, the flight with polarization filters were not performed before the 13th of March. The snow condition were not as wished since the snow surface had some slushy areas. The flights were performed in overcast weather. After the flights the pictures for each filter were sorted out and inserted to the Pix4D software. The result for all the models were more or less equal. The software partly managed to make a 3D model for each filter type where all models had some holes in them. The holes are there due to the program having trouble recognizing the pixels and therefore nothing is made in those places. Where the model successfully have been made there is many disturbing peaks, which make the model unusable. In general, the winter of 2018/2019 had less snow than earlier years, this made the test flight window quite narrow since the weather conditions needed to be as preferred for the flights.

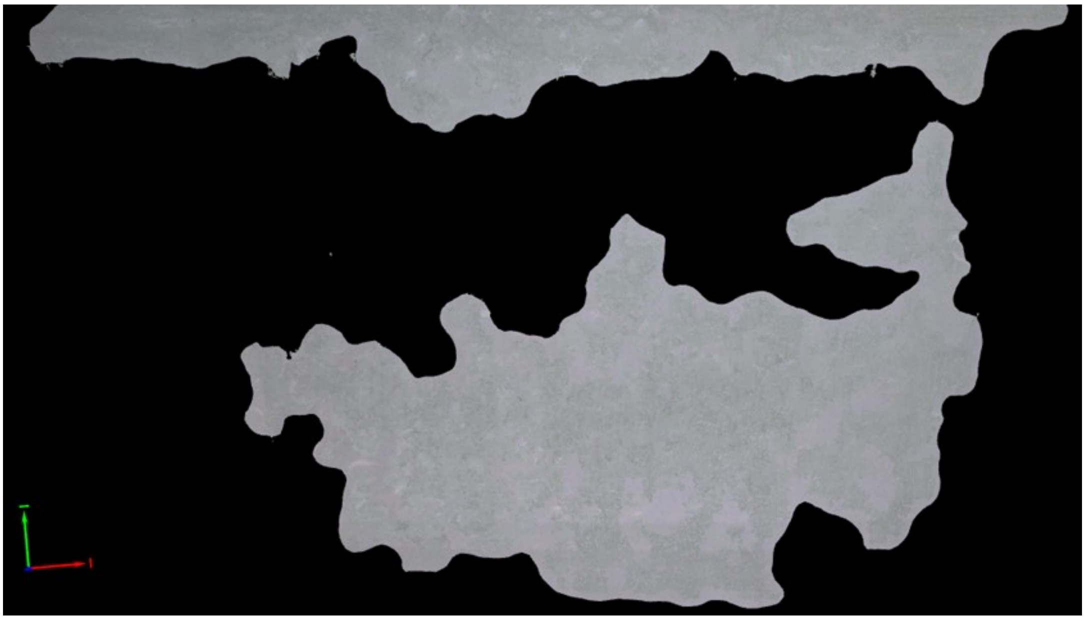

Figure 10: Obtained 3D model from photogrammetry with ND16/PL filter

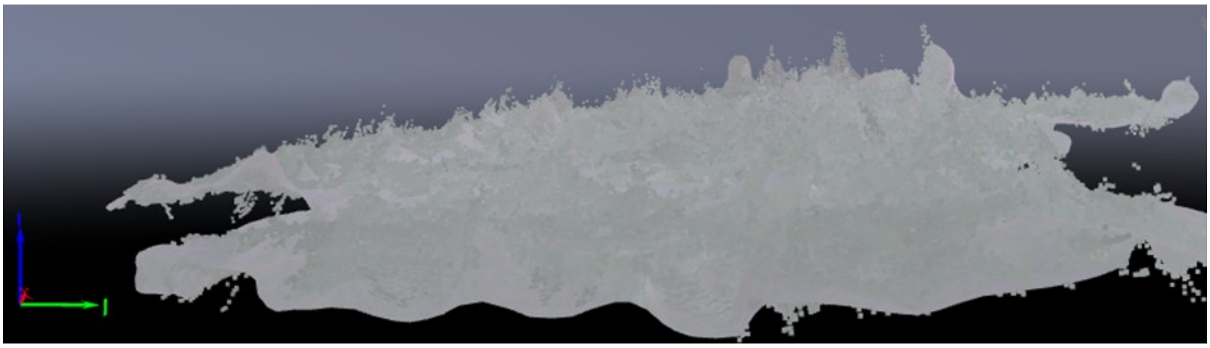

Figure 11: Peaks in 3D model from photogrammetry with ND16/PL filter

3.7 Winter flight

The winter flight was performed 28.02.2019 – 01.03.2019. On the 28th February Tjørhom and Flatstøl was performed, and Nesjen on the 1st March. Since the proposed camera settings for winter flights have a higher front and side overlap from earlier studies, this was also done in this project. Flight information is shown in the tables below for their respective area. From the previous experience from the summer flight when the iPad suddenly switched off it seemed necessary to protect the iPad from cold temperatures and wind, or at least be able to heat it up a bit. Several possible opportunities were suggested like a thermal vest, a neoprene cover for the iPad with a heating source inside or use of heating pads. A thermal west would make it unfeasible to move around with the controller if necessary, so this option was excluded. A neoprene cover for the iPad with heating source would be sufficient, but it might create some problems with attaching the cover sufficiently to the iPad with heating sources inside.

Therefore, simple heating pads that could be attached to the iPad with tape was found to be the best and most convenient solution to the problem.

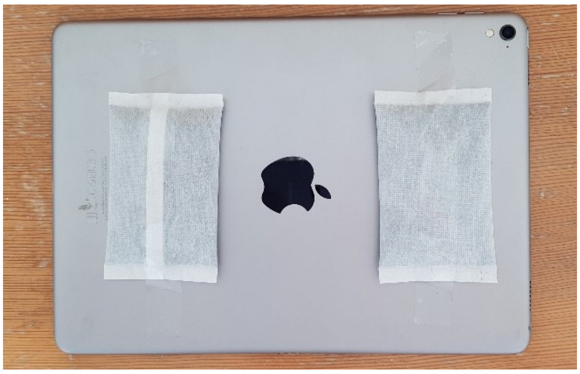

Figure 12: Heating pads as heating source attached to the iPad

3.7.1 Flatstøl

The flight was performed at 1.30 PM in sunny weather with 4°C. Since the drone batteries were not fully charged it was expected that the batteries would reach the limit of 18% as experienced in the summer flight, when the mission was paused and the drone returned by itself. That happened, but as with the summer flight it was easy to resume the mission after changing battery. To ensure that the heating pads had an important role by adding heat the iPad so it would stay on during the flights, it was tested to switch the iPad on without heating pads. It swithed on, but suddenly switched off after a few seconds. After adding heating pads, there were no issues with the iPad and it was constantly switched on. A third flight was started with higher overlap but did not finish due to the drone being out of battery. The third flight is not included since the overlap from the 1st and 2nd flight was sufficient to create a good model.

Table 4: Flight information from Flatstøl at winter survey

	Flight pattern	Altitude [m]	Area [m]	Camera angle	Front overlap	Side overlap
1. flight	Double grid	50	200x200	70°	70 %	50%
2. flight	Circular	50	200x200	70°	10 degrees between each picture	

3.7.2 Tjørhom

The winter flight at Tjørhom were performed on 28th of February, at 10 AM in sunny weather and 0°C. This flight was performed with the DJI Mavic 2 Pro drone provided by NTNU, since the iPad for the drone for Sira-Kvina was out of battery. The batteries to the drone from Sira-Kvina was also just around 50% charged. The reason for this is that the iPad and the drone was prepared some weeks before the flight would take place. The iPad was probably left on, and used it's battery over time, and the drone battery's start discharging after 10 days without use. (DJI, 2016) The map on the phone was less detailed than the map on the iPad, so it was decided to take a lunchbreak and charge the equipment for the drone from Sira-Kvina as much as possible before the flights at Flatstøl which was the next location.

Table 5: Flight information from Tjørhom at winter survey

	Flight pattern	Altitude [m]	Area [m]	Camera angle	Front overlap	Side overlap
1. flight	Double grid	50	100x100	70°	80 %	80%
2. flight	Circular	50	100x100	70°	10 degrees between each picture	

3.7.3 Nesjen

The flights on Nesjen were performed on the 1st of March in sunny weather at -3°C at 10 AM. At Nesjen a 3rd flight was performed as a backup to give the model more details if needed since the summer model had some holes in it. It turned out that two flights where sufficient to make a good model, so the 3rd flight is not included.

Table 6: Flight information from Nesjen at winter survey

	Flight pattern	Altitude [m]	Area [m]	Camera angle	Front overlap	Side overlap
1. flight	Double grid	50	130x200	70°	80 %	70%
2. flight	Circular	50	110x170	70°	10 degrees between each picture	

3.8 Creating 3D models in Pix4Dmapper

3D models in Pix4Dmapper are made by pixels being recognized in different images and transferred from 2D to 3D. To be able to use images they must be calibrated correctly. Correct calibration is obtained when the images have sufficient overlap, and the software is able to differentiate items in the image. Many trees or a field that looks similar can cause problems if there are nothing else in the image that can be recognized like roads. To match pixels, also called keypoints, there must be at least two images that shows some of the same area. To recognize keypoints they must have high contrast and contain interesting texture to get a possible match. According to Pix4D the minimum recommended number for keypoint matches in one picture is 1000. To secure that there would be similar points in the images, sufficient front and side overlap was applied before flying the missions. Each matched keypoint get its position calculated from the images that it is matched from and is placed in the point cloud where all matched keypoints are placed and together they make the 3D model. In Appendix B to F, the quality report from the processed 3D models is found. In the appendixes there is visualised were in the models the number of matched keypoints is high and low. More information from the processing of the 3D models is also found in Appendix B to F. To secure that both summer and winter models have the correct altitude according to each other, some fixed points in the models were selected as a control points and the altitude was corrected to obtain same elevation in the control points. Selection of control points was based on the wanted control point being visible and without snow in the winter model.

3.8.1 3D model at Flatstøl from summer survey

For the 3D model at Flatstøl 236 images were imported to Pix4Dmapper from the summer survey to create the model. In totalt 233 images were calibrated correctly and used. The three images that were not calibrated are located in the corner of the model an would not have any big impact for the total result. Pix4Dmapper managed to obtain a median of 70500 keypoints per image. From these keypoints, 25350 were matched. At maximum 79700 keypoints were found per image with 40140 matched keypoints, which tells that the number of keypoints matches found at Flatstøl is very good. (Pix4D support, 2019) The model obtained an average GSD of 2.16 cm, which gives a high quality model. From Figure 13 some black holes are visible in the model. These are spots where no keypoints were matched, and is left blank. The reason that some spots don't have matched keypoints is that the ground is too similar and it's hard to recognize similarities between pictures. On the small sideroad to the right in the model there are some blank spots. At this place there is a bunch of trees with a lot of leaves. Many leaves look the same and it is therefore hard to match keypoints in this area. Some places the ground and the tree trunk is visible and a few points are recognized pixels from leaves and projected above the ground. Close to those trees, there are some minor holes in the model. Without the whole tree reproduced in the model, it will lead to a negative value in the volume calculations if more of the tree is visible in the winter model.

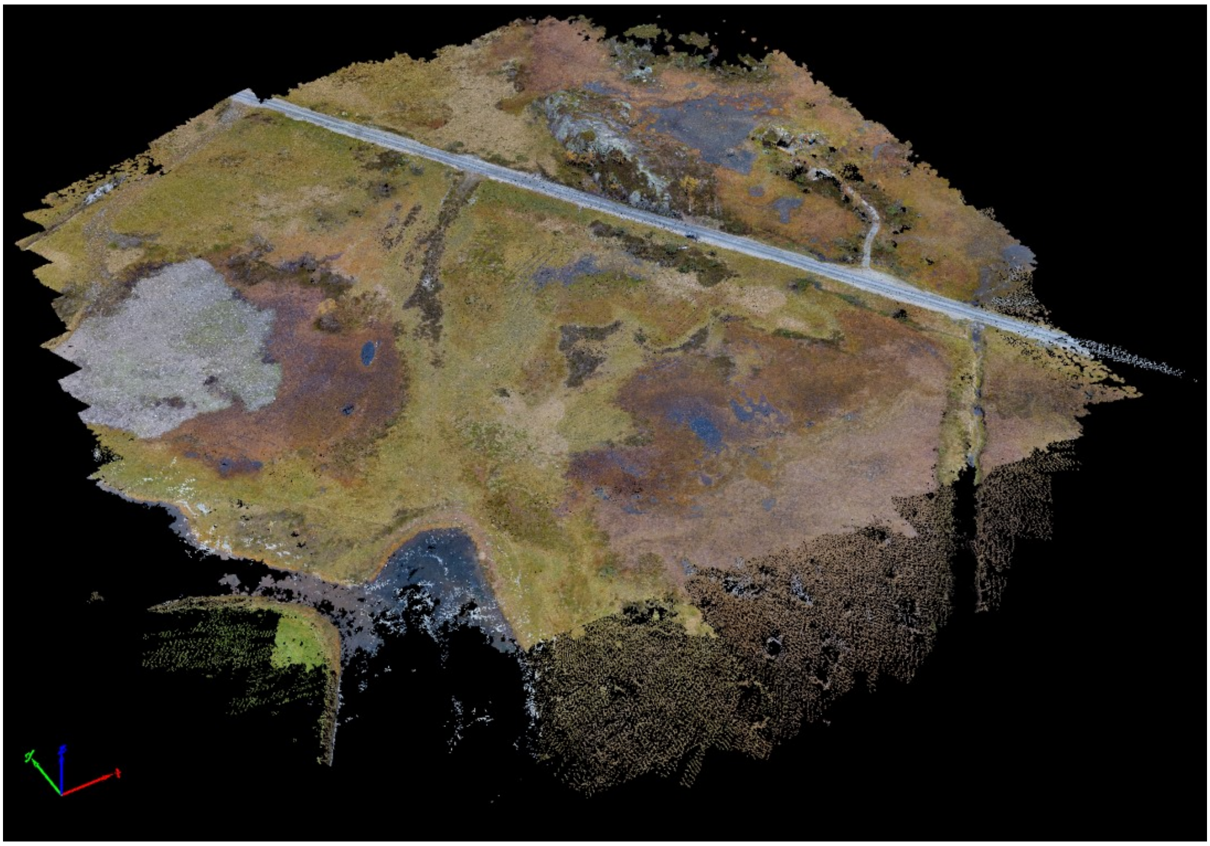

Figure 13: Summer 3D model at Flatstøl

3.8.2 3D model at Flatstøl from winter survey

From the winter survey at Flatstøl 226 images were imported to the model and all of them were correctly calibrated. A median of 23280 keypoints were found per image and 10470 of those were matched. At maximum 42600 keypoints were found and 23860 were matched. The average GSD is 2.15 cm. This model have less holes since there are no leaves on the trees, but still there are some trees that stand close to each other and the software have trouble to differentiate these and therefore no matches are found. Disturbance from shadows in this model are minor but some disturbance is visible in larger shadowed areas as behind a hillside and a cabin in the model. When both models for Flatstøl were made, a geolocation check was performed since the projects does not contain any GCP's. With the summer model as reference, the winter model at Flatstøl had an offset of +0.18 m in x direction and -0.59 m in y-direction according to the summer model. Since Flatstøl in general is a relative flat area, the offset is believed to not have much impact on the result, but the result is therefore not completely accurate.

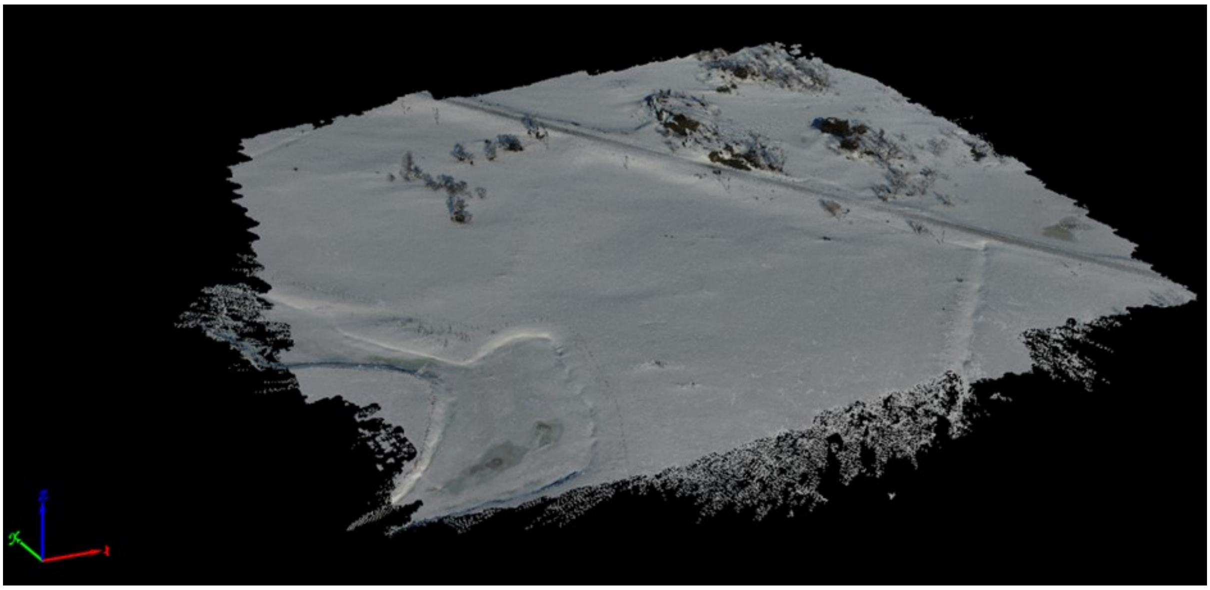

Figure 14: Winter 3D model at Flatstøl

3.8.3 3D model at Tjørhom from summer survey

At Tjørhom 161 images were imported to Pix4Dmapper and all of them were correctly calibrated. A median of 69830 keypoints were found and 28400 of those were matched per image. At maximum there were 79780 keypoints with 41160 matches. This also gives a model of high quality. Since the summer flight at Tjørhom was performed in different altitudes, a GSD of 1.77 cm was obtained.

Figure 15: Summer 3D model at Tjørhom

3.8.4 3D model at Tjørhom from winter survey

As mentioned in capter *3.7.2 Tjørhom* the winter survey at Tjørhom was performed with the DJI Mavic 2 Pro drone. 206 images were taken and 204 of them were correctly calibrated. After importing the images into Pix4Dmapper and running the processing steps, it turned out that the GPS on the drone was not correctly calibrated. The drones position was in general divided into 4 different areas as visualized in Figure 16 from the GPS position of the images. The result of the inaccurate GPS position for the images was a highly disturbed model. A small part of the model looks good, but the rest of the images seem to have been put together in a messy area a bit over the good looking part. Accuracy of GPS coordinates is important to be able to process models correctly. Pix4D also mention that with GPS coordinates the processing time for the model will be faster since the model then knows which images that possibly share some of the same pixels. (Pix4D SA, 2019)

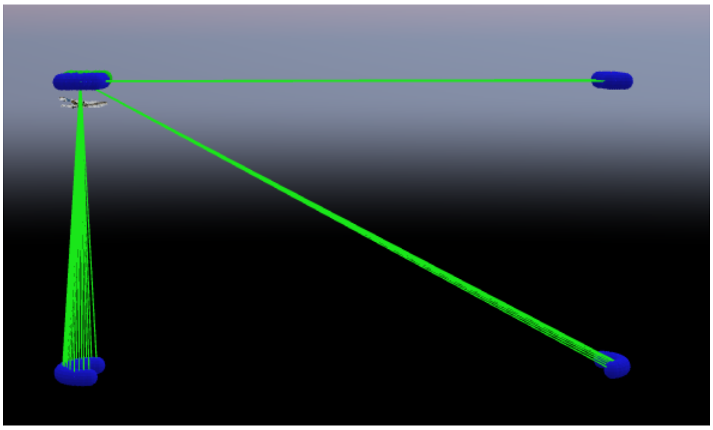

Figure 16: Camera positions visualised with blue dots

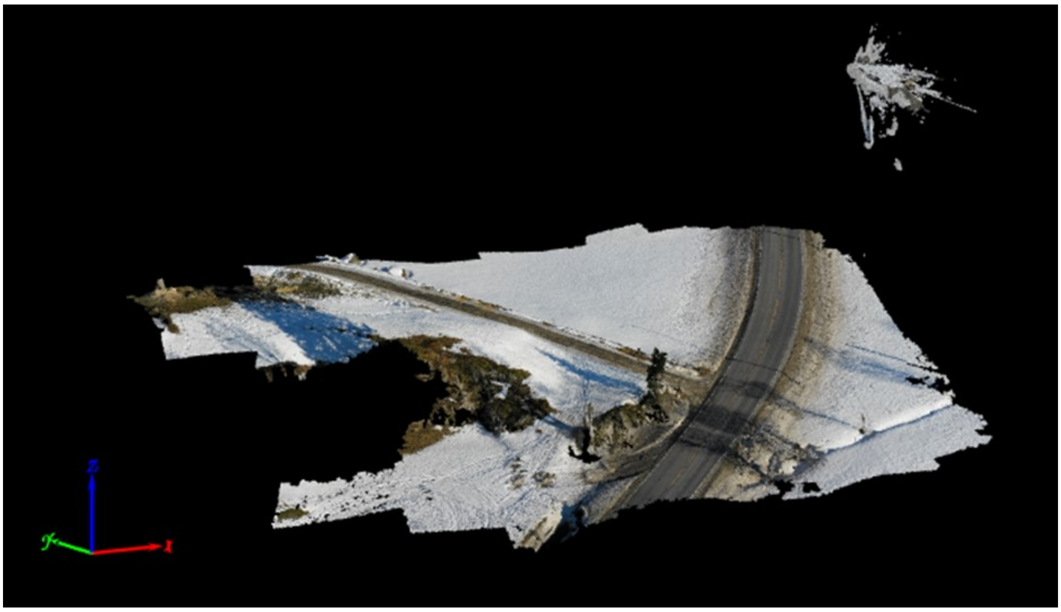

Figure 17: Winter 3D model at Tjørhom

Since the winter model at Tjørhom was not successfully processed, Kaspar Vereide in Sira-Kvina power company performed a new flight with the DJI Phantom 4 drone. Due to limited available time the flight was performed in overcast weather condition. From the earlier surveys in this thesis, overcast weather condition is not suitable for photogrammetry with drone. After receiving the images and processing them, the result was as expected. In areas where there is snow, everything looks similar due to the light reflection and the Pix4D software is not able to recognize similar pixels. Only road surfaces, vegetation between fields and power lines are visible as seen in Figure 18. The powerline that is visible in the model also have much snow disturbance around it. The quality report generated after the processing of this model is found in Appendix F where the lack of calibrated cameras are visualized, and other parameters from the flight are found. Since the attempts to create a winter model was not successful, volume calculation from Tjørhom would be neglected in this thesis.

Figure 18: Winter 3D model at Tjørhom after second flight

3.8.5 3D model at Nesjen from summer survey

The 3D model for Nesjen in the summer is the model with the highest number of images used to create the model. 237 images were imported to the model and all of them were calibrated correctly. The median keypoint number is 54800 were 23360 of them were matched. At maximum 62990 keypoints were found and 36060 of them were matched with other images. The average GSD at Nesjen is 1.74 cm. From Figure 19 there are many holes in the model on the right side of the road. This is because the terrain in this area is very steep and the drone had it's outer position just above the road during the flights. The terrain to the right of the model is captured as well due to the camera angle on the drone. On the left side of the model there are also a small lake that has some empty spots. This is most likely due to the fact that the surface of the lake could change between each taken image due to small waves or the water surface being too similar and therefore similar pixels is not obtained.

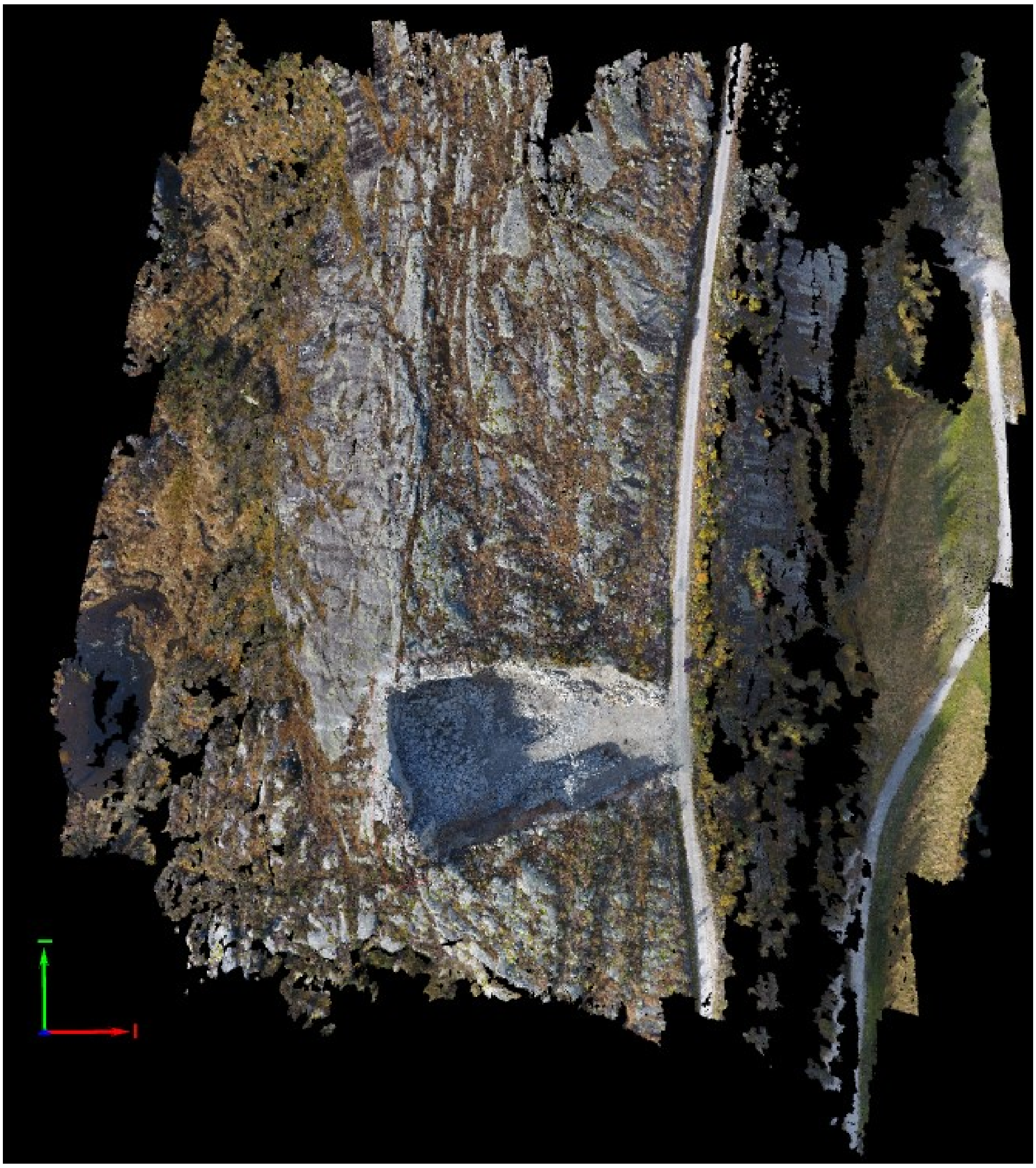

Figure 19: Summer 3D model at Nesjen

3.8.6 3D model at Nesjen from winter survey

In the winter survey at Nesjen 226 images were captured. From these 225 were calibrated and usable. The uncalibrated image is to the left in the model. It is probably uncalibrated due to that no other images are taken on the same spot or in the same direction, even if the chosen overlap should be sufficient. The median number of keypoints per image is 48640 per image and 21220 of them are matched. At maximum 49000 keypoints were found and 21180 of theme were matched. The number of matched keypoints at Nesjen is around twice as many as matched keypoints in the winter model from Flatstøl. This is probably due to that at Nesjen there is more bare ground in between the snow, so it is easier to recognize pixels. The average GSD at Nesjen in wintertime is 1,38 cm. This is the lowest obtained GSD from the surveys in this thesis. In the small quarry to the left in the model there is a blank spot in an area with shadow. That can be caused by the shadow making the area darker and because of that it is harder to recognize similar pixels. In the shadowed area, there is also some disturbing peaks. After controlling elevation in fixed spots in each models at Nesjen it seems like the models were a bit twisted according to each other, which will be useless for volume calculation. The same as Flatstøl, Nesjen also had an offset for the geolocation. With the summer model as reference, the winter model at Nesjen had an offset of -0.39 m in x direction and -0.02 m in y-direction according to the summer model. Since Nesjen is a more hilly area than Flatstøl the impact of the volume calculation will be greater and more unreliable.

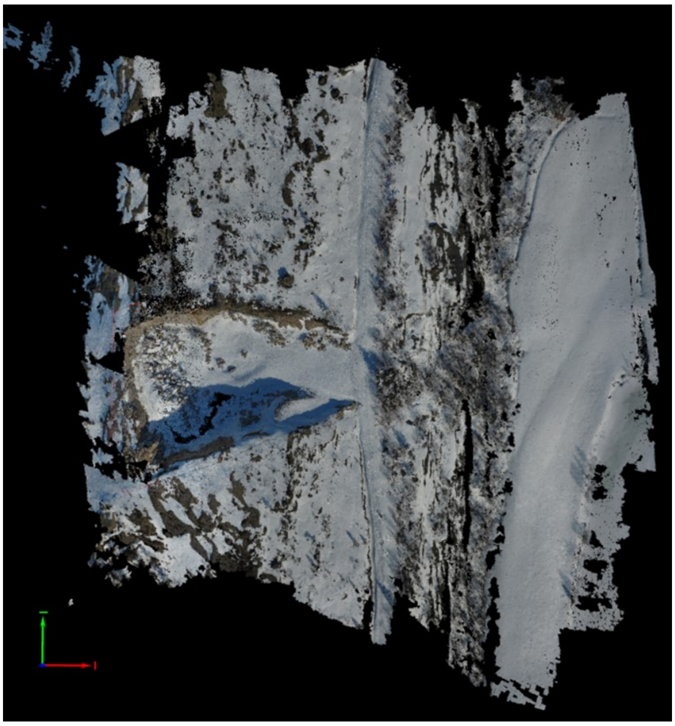

Figure 20: Winter 3D model at Nesjen

4 Results

Performing volume calculation in Pix4Dmapper between two models was found to not be a feasible solution. When an object was drawn in the bare ground 3D model that was supposed to work as a base surface in the volume calculation, the object came out as a flat plane, which is not sufficient. To calculate the snow volume, the point cloud from Pix4Dmapper was exported to an .xyz file and imported into the CloudCompare software. CloudCompare is a software were the user, for instance can calculate the volume between two point clouds, which is the wanted result for the author.

4.1 Snow volume at Flatstøl from CloudCompare

To avoid places in the model with larger holes an area of 140x190 meters was chosen. The chosen area is consisting of a small hill, the road and a part of the flat area. The area is visualized in Figure 22. The volume in CloudCompare is found by calculating the height difference in similar coordinates. By taking $H_{Winter} - H_{Summer}$ from the Z-coordinates, the height difference between each point is found and the volume is calculated from that. Since the coordinates is expressed in meters, the output from CloudCompare is also in meters. (Girardeau-Montaut, 2014) The two point clouds placed on top of each other in CloudCompare is visible in Figure 21. In Figure 21 trees from the summer survey is also visible since almost all the trees are higher than the snow height. High trees with leaves on from the summer survey are then appearing over the snow surface.

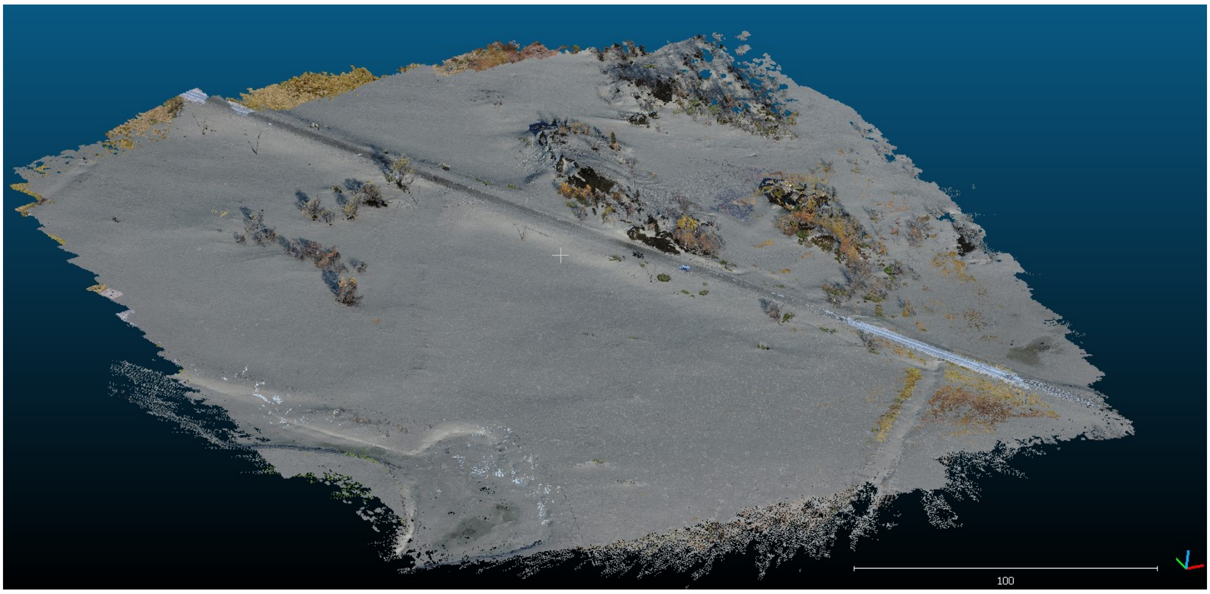

Figure 21: Winter 3D model at Flatstøl placed over summer 3D model

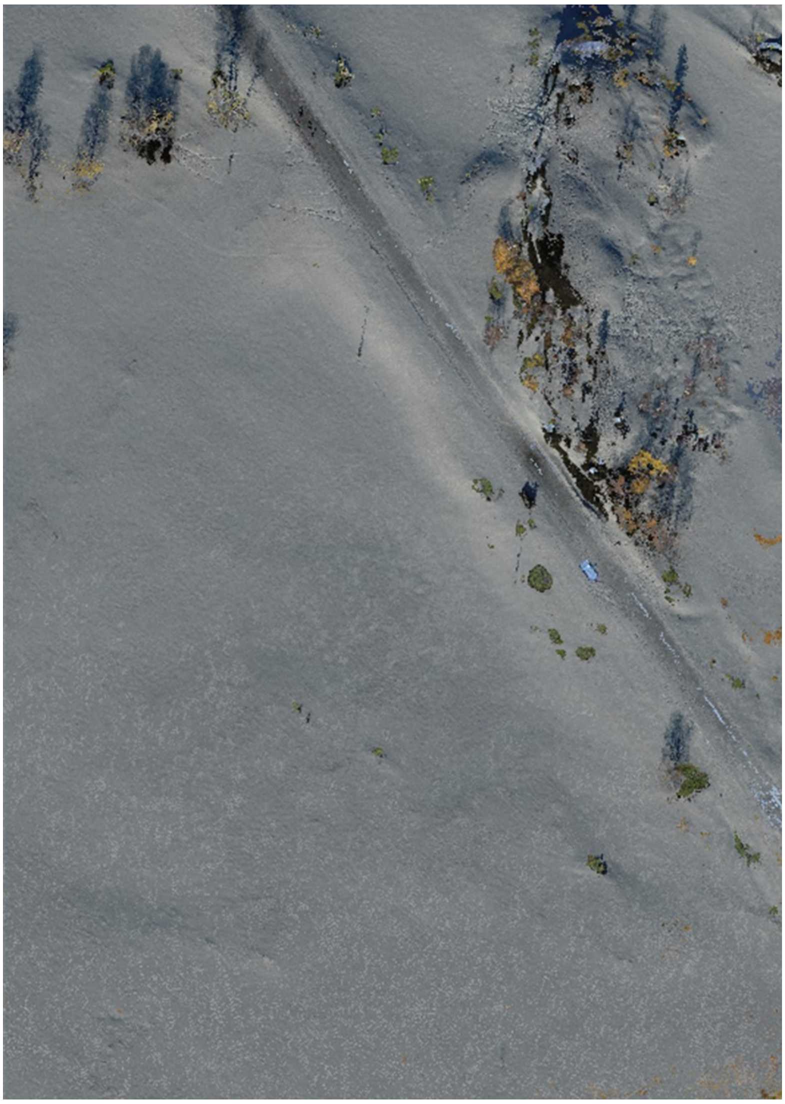

Figure 22: Area from winter 3D model and summer 3D model at Flatstøl used for volume calculation

The result from the volume calculations in the 140x190 meter large area tells that there is a snow volume of 12 853.5 m^3 of snow. The total area is 26 600 m^2 which gives an average snow height of 0.48 meters. The manual measurement performed at Flatstøl showed a snow depth of 0.35 metres, and when calculating volume with basic mathematic rules over the area by taking area times snow height, a snow volume of 9310 m^3 is obtained. With drone, the snow distribution is more covered and there is an increase in snow volume of 38% with the drone measurements. It is important to keep in mind that the obtained mean snow depth of 0.48 meters from CloudCompare is the mean depth of all measurements done in the area. There is both positive and negative peaks because of trees in the volume calculation that would affect the mean value. The manual measurement is done at one “random” spot in a flat area at Flatstøl. The increase shows that manual measurements give less snow than the volume obtained from the measurements performed with drones. At Flatstøl the vegetation had some grass, but the grass was not dense and should not affect the volume calculation, but there is of course a chance that minor affects occurs. The snow distribution on Flatstøl is mostly varying between 0 and 1 meters. Some places $H_{Winter} - H_{Summer}$ is a negative value and the reason is because of trees with leaves in the summer have a higher Z value than the Z value at the same point in wintertime. There is also cases where the leaves are not visible in the summer model and it is just the ground that is visible below, while the tree trunk is visible in the winter model, and by that it causes a much higher Z value than it is in reality.

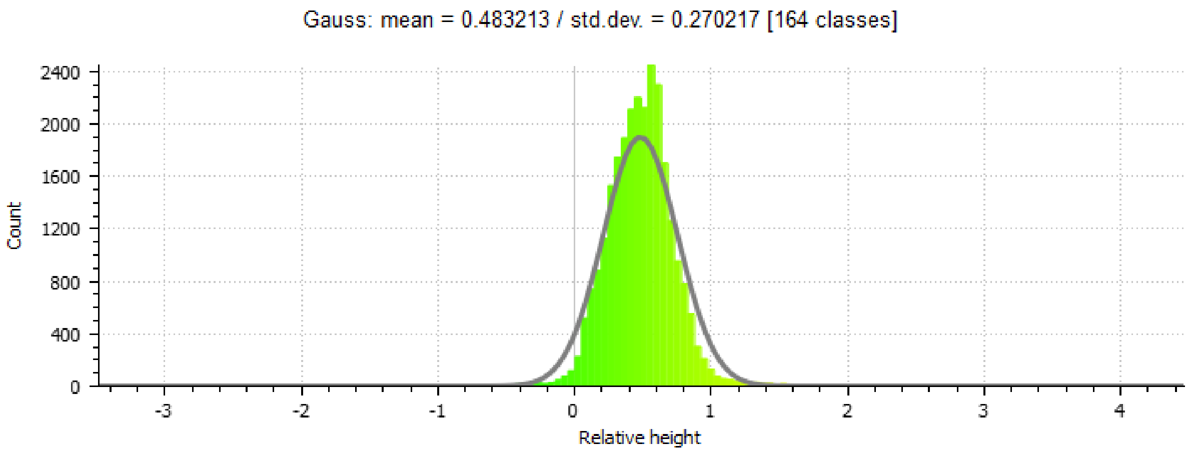

Figure 23: Snow distribution at Flatstøl obtain from 3D models

The manual measurement was performed close to a ski track, south-west from the snowmobile to easily be able to locate the measurement point in the model since no GPS measurement equipment was brought and the drone was out of battery. To control the snow depth in the model five spots close to each other at the measurement site were chosen. The control spots forms a square with a point in each corner and a point in the middle of the square as seen in Figure 24. At each point, the calculated snow depth from the models in Pix4Dmapper is stated. The distance from the centre point and to the points forming the square is around one meter. The obtained snow depth in these spots from the 3D models in Pix4Dmapper shows that the snow depth obtained in the model is good according to the manual measurements, which verifies that the computed snow volume from CloudCompare is pretty reliable.

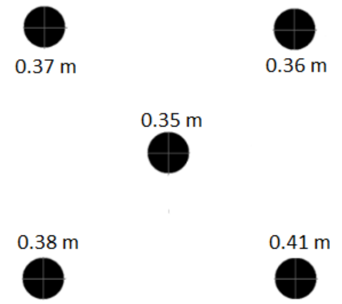

Figure 24: Snow depth at measurement spot obtained from 3D models

When volume is calculated in CloudCompare, the result also tells how many neighbouring pixels that was found on average. Since one pixel have 8 neighbouring pixels as long as it is not on the outer edge it is wished to achieve a number as close to 8 as possible. From the calculation at Flatstøl the average neighbouring cells were 8 which is maximum. Since the maximum number of neighbouring cells were obtained, it tells that the selected area in the 3D models used for volume calculation is dense and without holes which make them very representative for volume calculation.

To find the snow volume without measure SWE manually would save time when working in the field. The SWE could be obtained either from interpolation between SWE measurement stations in Norway or calculating it from a formula. From the interpolated values from the SWE measurement stations, the SWE at Flatstøl on the 28th of February was 96.6 mm. (NVE, et al., 2019) This value is quite much lower than the measured SWE value on 119.2 mm, and would be considered as to unreliable. Each interpolated cell is 1 km^2 large, and from the neighbouring cells from the measurement spot the SWE in the interpolated cells are ranging from 95.6 mm to 292.8 mm. In 7 out of 8 cells the SWE is larger than 200 mm which confirms that these interpolated values are not reliable. Tests on calculating the density of the snow without measuring it has been carried out, but it is not a strait forward calculation. The snow density (ρ_s) is dependent on the snow height, snow temperature, history of deposition of snow and density of initial snow layers. (Sturm, et al., 2010) Since these parameters are hard to achieve, the theoretical calculation for SWE will not be further investigated in this thesis.

4.2 Snow volume at Nesjen from CloudCompare

At Nesjen the point cloud from Pix4Dmapper was exported to an .xyz file similar to Flatstøl. After importing the point clouds to CloudCompare it was easy to see that the point clouds were slightly twisted according to each other, as expected from the controls in Pix4Dmapper. As Figure 25 shows, the model seems to have snow cover in one part and it is snow free in the other part. With a twisted point cloud, volume calculation can not be performed since the results will be wrong and not reliable. No correction solution to align models correctly without GCP was found in the Pix4Dmapper software. There are no cases were two models from the same site, where one is with snow and the other is without snow, were compared.

Figure 25: Section of winter 3D model placed above summer 3D model at Nesjen

4.3 Economic impact of snow measurements with drones

From Flatstøl the snow measurement from the drone showed an increase in snow storage of 38% according to the manual measurements. The increased snow storage shows that there will be more water than first expected to produce electric power from and more income can therefore be generated. Comparing the two measurement methods gives the following volumes over the surveyed area:

Table 7: Comparison of results between manual measurements and drone measurements

Flatstøl	Snow height (m)	SWE (mm)	Area (m^2)	Snow volume (m^3)	Water volume (m^3)
Manual measurement	0.35	119.2	26 600	9310	3170.72
Drone measurement	0.48	163.4	26 600	12 853.5	4346.44

The drone measurements show an increase in calculated runoff of 1175.72 m^3 over the 26 600 m^2 large survey area. By assuming that the difference in snow volume and calculated runoff between drone and manual measurements is linear, an increase in calculated runoff per square kilometre is 44 200 m^3 with a SWE of 163.4 mm.

Due to that data for snow storage in the Sira-Kvina catchment area was not accessed, assumptions for the increased income has to be made. Sira-Kvina Power Company have a total catchment area of 2700 km^2, and by assuming that the calculated increase in expected runoff is valid for half of Sira-Kvina's catchment area, an area of 1350 km^2 is obtained. That gives in total 59.67 million m^3 in additional expected water runoff in the calculations, which would give opportunities for better planning of use of reservoirs. Sira-Kvina then gets possibilities to produce more when there is high demand in the market and can earn more money. Given a scenario with a power plant with a net head of 100 meters, a turbine efficiency of 0.92 and an extra income of 0.10 NOK/KWh since the water can be used for production when there is high demand. For calculation simplicity, the water is equally divided over one year with the power plant running constantly and assuming an extra earning of 0.10 NOK/KWh all the time. On the 59.67 million m^3 of water, the power plant would generate 14.96 GWh in one year with 0.10 NOK/KWh more in income from production. The expected income before tax is then 1.496 mill NOK. The effect of the possibility for better operation of the reservoir is therefore quite large. The increased calculated runoff would probably not be correct for the whole 1350 m^2

large area, but it gives an idea that with better reservoir operation, more income could be generated with more accurate snow measurements.

Since the hydropower system in Sira-Kvina is combined and the water is used more than once in different power plants, the real increased income would be higher. There is a need for more complex calculations for operation of all the reservoirs and power plants to find the approximate total possible increase in income. These complex calculations will not be investigated in this thesis.

5 Conclusion

Snow measurement with drone is an interesting new technology, but also a time demanding topic. Snow measurement with drones is a great opportunity to perform snow measurement over larger areas and cover differences in snow accumulation to obtain a more accurate snow volume. Performance of drone photogrammetry with snow on the ground have been investigated and to make sufficient 3D models there is a need of sunny weather to be able to create good 3D models without empty spots. Creation of 3D models that was performed in Pix4Dmapper had very good numbers of obtained matched keypoints, which made nice and clear 3D models in general. In the models there are less disturbance from shadow when the sun is standing high on the sky in comparison to a low sun. The 3D models from Flatstøl gave a good base to perform volume calculations in CloudCompare and compare these results according to results from manual measurments. The improved snow measurement with drones gives possibilities for better operation of reservoirs and by that Sira-Kvina can get more income by producing more when there is high demand.

6 Proposal for future work

Further work should investigate more on possibilities to take pictures in different weather conditions without sun. If there is a way to obtain good and reliable 3D models when the photogrammetry have been performed in overcast weather there will be more opportunities to perform the photogrammetry on snow without being dependent on the weather conditions.

In this thesis GCP was not used, since it demand proper measurement equipment. It is interesting to investigate how much measurements will be affected if GCP's are added and centimetric accuracy can be obtained. If GCP's should be used, there should also be sufficient time to place out and measure all spots. Time can be a problem if many places need to be surveyed in a short amount of time due to limitations in good weather conditions.

During flight, dense forest and larger shadowed areas should be captured from a lower altitude to obtain more details and by that obtaining a better 3D model.

By using a hexacopter, a larger camera with higher image resolution could be attached. If even better details in the 3D models are obtained and how much longer the processing time of the models would be is interesting.

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Appendix A – Manual measurement results

REGISTRERING

Målingen er utført i tiden: 28/2 - 1/3 2019

Velg vekting / middel (V/M)		V	Sylind. (52/90)	52	Areal 0,97	dm²	Vekt 3,55 Kg						
Måling (1/2) 1	Ned-	Dato	Snødybde		Vekt							Sum	Vann
Målested	bør		Felt	Sted	1.	2.	3.	4.	5.	6.	7.	vekt	%
03 Håhelleren													
02 Skrubbsløkjen													
01 Bottsvann													
07 Rjuven													
12 Grautheller													
09 Auråhorten													
10 Kringlevann													
14 Flatstøl		28/2	0,35	0,33	4,64							4,64	34,1
18 Instestøl													
20 Grubbå													
04 Omlibastog													
08 Holmevann													
05 Eivindvann													
06 Landsløk / Nesjen		1/3	0,40	0,40	4,97							4,97	36,6
15 Grunnetjørn													
19 Vassfelltjørnene													
16 Flæene													
17 Tjørhom		28/2	0,20	0,19	4,16							4,16	33,1
Snømagasin til Tonstad		Mill.m³		I forhold til middel	(1971	til	2019)	0,0 %		Middel vanninnhold			35,8 %

REGISTRERING AV SNØMÅLINGER

Stasjon	Dato	Snødyp (cm)	Tetthet (kg/m³)	Vannekv. (mm)
Skrubbsløkjen	[redacted]			
Bottsvann	[redacted]			
Håhelleren	[redacted]			
Omlibastog	[redacted]			
Eivindvann	[redacted]			
Landsløk / Nesjen	01.03.2019	40	366,0	146
Kringlevann	[redacted]			
Rjuven	[redacted]			
Vassfelltjørnene	[redacted]			
Auråhorten	[redacted]			
Grubbå	[redacted]			
Grautheller	[redacted]			
Holmevatn	[redacted]			
Flatstøl	28.02.2019	35	340,5	119
Grunnetjørn	[redacted]			
Tjørhom	28.02.2019	20	331,0	66
Innstestøl	[redacted]			
Flæene	[redacted]			

Tetthet = vanninnhold i % x 10

Vannekvivalent = Snødyp (cm) x Tetthet (kg/m³)/100

Appendix B – Quality report from summer survey at Flatstøl

Quality Report

Generated with Pix4Dmapper version 4.3.33

Important: Click on the different icons for:

Help to analyze the results in the Quality Report

Additional information about the sections

Click here for additional tips to analyze the Quality Report

Summary

Project	Flatstolprosjekt
Processed	2019-05-06 17:09:44
Camera Model Name(s)	FC330_3.6_4000x3000 (RGB)
Average Ground Sampling Distance (GSD)	2.16 cm / 0.85 in

Quality Check

Images	median of 70517 keypoints per image	
Dataset	233 out of 236 images calibrated (98%), all images enabled	
Camera Optimization	3.44% relative difference between initial and optimized internal camera parameters	
Matching	median of 25352.5 matches per calibrated image	
Georeferencing	yes, no 3D GCP	

Calibration Details

Number of Calibrated Images	233 out of 236
Number of Geolocated Images	236 out of 236

Initial Image Positions

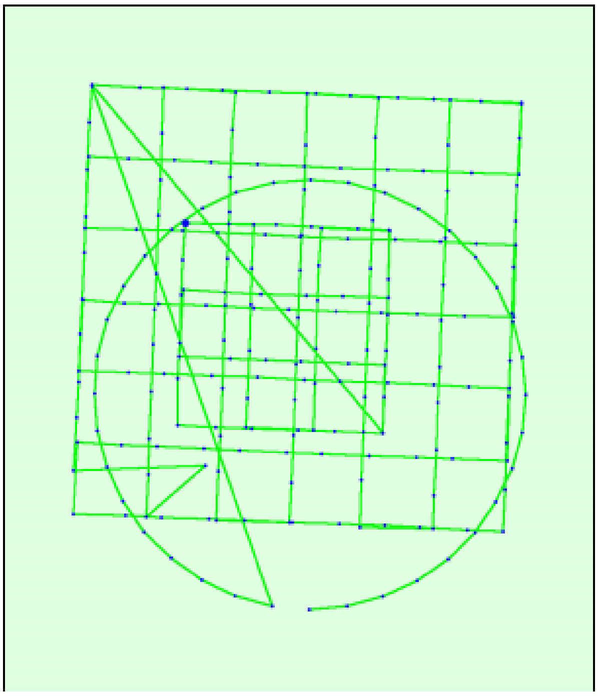


Figure 2: Top view of the initial image position. The green line follows the position of the images in time starting from the large blue dot.

Computed Image/GCPs/Manual Tie Points Positions

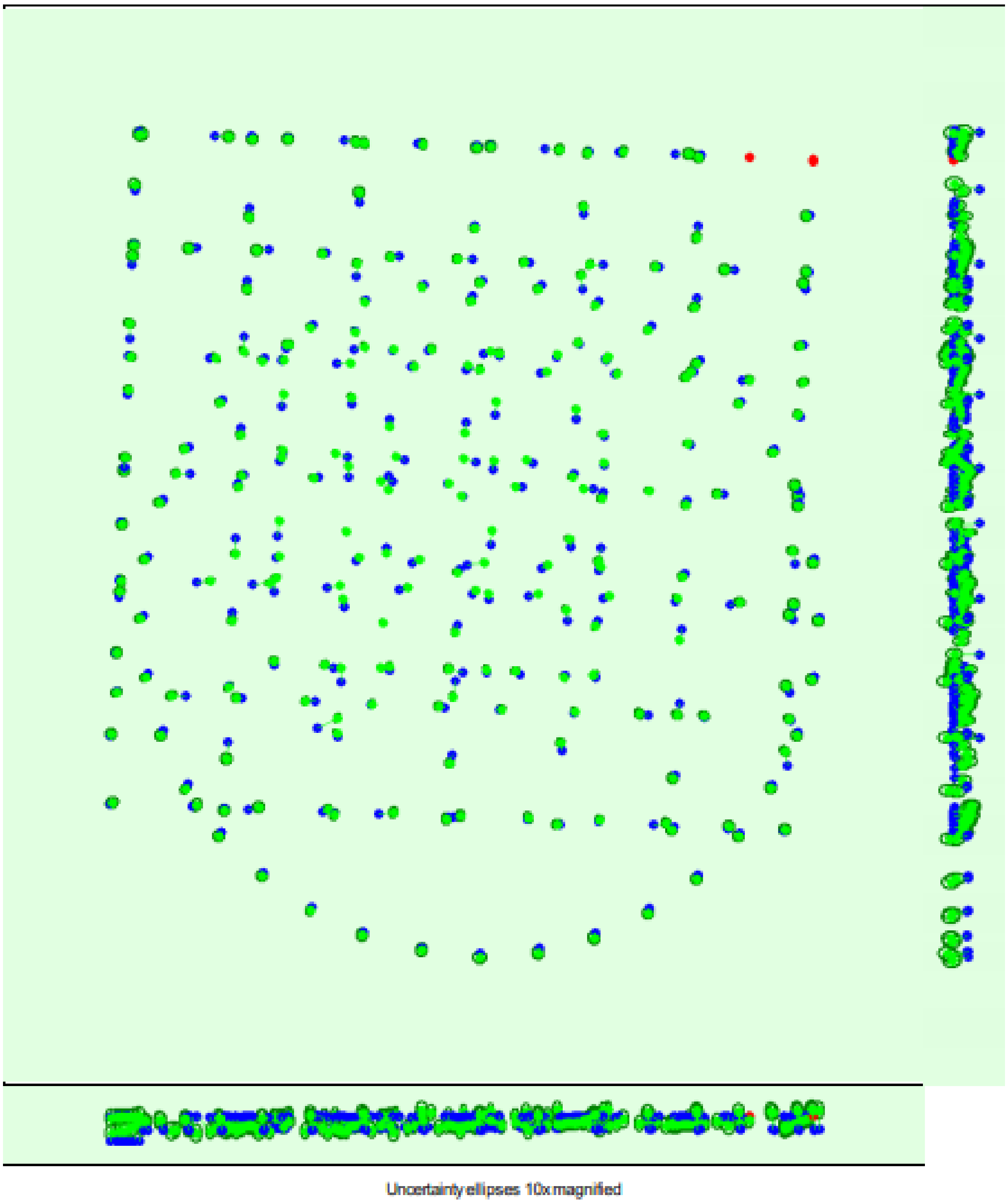


Figure 3: Offset between initial (blue dots) and computed (green dots) image positions as well as the offset between the GCPs initial positions (blue crosses) and their computed positions (green crosses) in the top-view (XY plane), front-view (XZ plane), and side-view (YZ plane). Red dots indicate disabled or uncalibrated images. Dark green ellipses indicate the absolute position uncertainty of the bundle block adjustment result.

Absolute camera position and orientation uncertainties

	X[m]	Y[m]	Z[m]	Omega [degree]	Phi [degree]	Kappa [degree]
Mean	0.131	0.131	0.218	0.071	0.070	0.069
Sigma	0.021	0.022	0.016	0.012	0.006	0.023

Bundle Block Adjustment Details

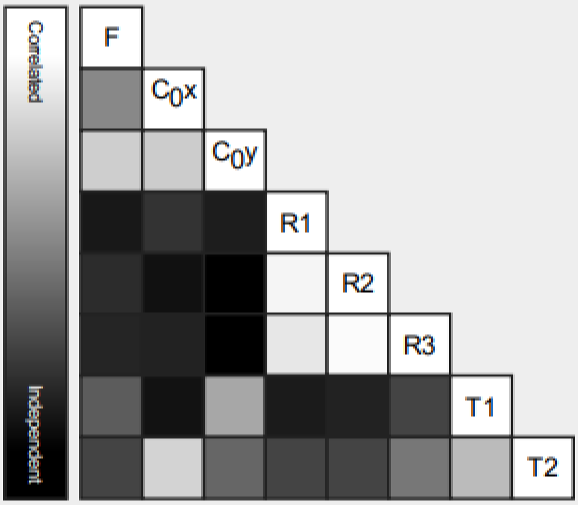
Number of 2D Keypoint Observations for Bundle Block Adjustment	6028566
Number of 3D Points for Bundle Block Adjustment	2414365
Mean Reprojection Error [pixels]	0.193

Internal Camera Parameters

FC330_3.6_4000x3000 (RGB). Sensor Dimensions: 6.317 [mm] x 4.738 [mm]

EXIF ID: FC330_3.6_4000x3000

	Focal Length	Principal Point x	Principal Point y	R1	R2	R3	T1	T2
Initial Values	2285.722 [pixel] 3.610 [mm]	2000.006 [pixel] 3.159 [mm]	1500.003 [pixel] 2.369 [mm]	-0.001	-0.002	0.000	-0.001	-0.001
Optimized Values	2364.543 [pixel] 3.734 [mm]	2069.555 [pixel] 3.269 [mm]	1519.960 [pixel] 2.401 [mm]	-0.003	-0.005	0.003	0.000	0.001
Uncertainties (Sigma)	0.125 [pixel] 0.000 [mm]	0.048 [pixel] 0.000 [mm]	0.080 [pixel] 0.000 [mm]	0.000	0.000	0.000	0.000	0.000



The correlation between camera internal parameters determined by the bundle adjustment. White indicates a full correlation between the parameters, ie. any change in one can be fully compensated by the other. Black indicates that the parameter is completely independent, and is not affected by other parameters.

The number of Automatic Tie Points (ATPs) per pixel, averaged over all images of the camera model, is color coded between black and white. White indicates that, on average, more than 16 ATPs have been extracted at the pixel location. Black indicates that, on average, 0 ATPs have been extracted at the pixel location. Click on the image to the see the average direction and magnitude of the re-projection error for each pixel. Note that the vectors are scaled for better visualization. The scale bar indicates the magnitude of 1 pixel error.

2D Keypoints Table

	Number of 2D Keypoints per Image	Number of Matched 2D Keypoints per Image
Median	70517	25353
Min	47761	3931
Max	79697	40139
Mean	68803	25874

3D Points from 2D Keypoint Matches

	Number of 3D Points Observed
In 2 Images	1792484
In 3 Images	378090
In 4 Images	123782
In 5 Images	51845
In 6 Images	25840
In 7 Images	14393
In 8 Images	8714
In 9 Images	5471
In 10 Images	3739
In 11 Images	2723
In 12 Images	1812
In 13 Images	1289
In 14 Images	945
In 15 Images	705
In 16 Images	520
In 17 Images	388
In 18 Images	305
In 19 Images	248
In 20 Images	199
In 21 Images	173
In 22 Images	129
In 23 Images	119
In 24 Images	104
In 25 Images	89
In 26 Images	58
In 27 Images	51
In 28 Images	36
In 29 Images	19
In 30 Images	25
In 31 Images	11
In 32 Images	17
In 33 Images	13
In 34 Images	12
In 35 Images	3
In 36 Images	3
In 37 Images	3
In 38 Images	3
In 39 Images	2
In 41 Images	2
In 43 Images	1

2D Keypoint Matches

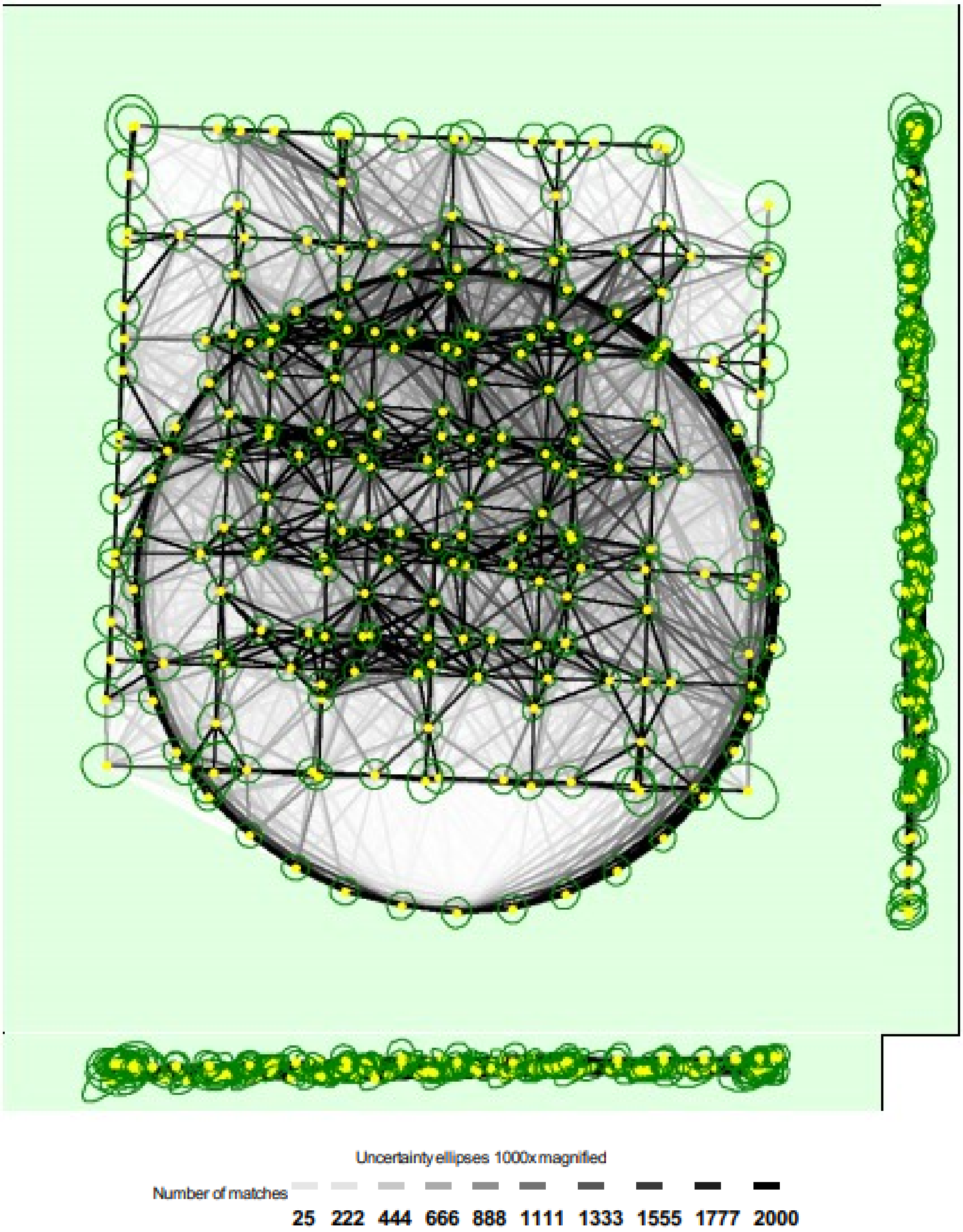


Figure 5: Computed image positions with links between matched images. The darkness of the links indicates the number of matched 2D keypoints between the images. Bright links indicate weak links and require manual tie points or more images. Dark green ellipses indicate the relative camera position uncertainty of the bundle block adjustment result.

Relative camera position and orientation uncertainties

	X[m]	Y[m]	Z[m]	Omega [degree]	Phi [degree]	Kappa [degree]
Mean	0.004	0.004	0.003	0.005	0.004	0.003
Sigma	0.001	0.001	0.001	0.002	0.002	0.001

Geolocation Details

Absolute Geolocation Variance

Min Error [m]	Max Error [m]	Geolocation Error X [%]	Geolocation Error Y [%]	Geolocation Error Z [%]
-	-15.00	0.00	0.00	0.00
-15.00	-12.00	0.00	0.00	0.00
-12.00	-9.00	0.00	0.00	0.00
-9.00	-6.00	0.00	0.00	4.29
-6.00	-3.00	6.01	5.15	24.46
-3.00	0.00	36.05	42.49	11.16
0.00	3.00	54.08	47.64	41.20
3.00	6.00	3.86	4.72	18.88
6.00	9.00	0.00	0.00	0.00
9.00	12.00	0.00	0.00	0.00
12.00	15.00	0.00	0.00	0.00
15.00	-	0.00	0.00	0.00
Mean [m]		0.000005	-0.000006	0.000031
Sigma [m]		1.531214	1.529028	3.371997
RMS Error [m]		1.531214	1.529028	3.371997

Min Error and Max Error represent geolocation error intervals between -1.5 and 1.5 times the maximum accuracy of all the images. Columns X, Y, Z show the percentage of images with geolocation errors within the predefined error intervals. The geolocation error is the difference between the initial and computed image positions. Note that the image geolocation errors do not correspond to the accuracy of the observed 3D points.

Relative Geolocation Variance

Relative Geolocation Error	Images X [%]	Images Y [%]	Images Z [%]
[-1.00, 1.00]	99.57	100.00	100.00
[-2.00, 2.00]	100.00	100.00	100.00
[-3.00, 3.00]	100.00	100.00	100.00
Mean of Geolocation Accuracy [m]	5.000000	5.000000	10.000000
Sigma of Geolocation Accuracy [m]	0.000000	0.000000	0.000000

Images X, Y, Z represent the percentage of images with a relative geolocation error in X, Y, Z.

Geolocation Orientational Variance	RMS [degree]
Omega	2.295
Phi	4.146
Kappa	8.225

Geolocation RMS error of the orientation angles given by the difference between the initial and computed image orientation angles.

Initial Processing Details

System Information

Hardware	CPU: Intel(R) Core(TM) i7-2600 CPU @ 3.40GHz RAM: 8GB GPU: AMD Radeon HD 5450 (Driver: 15.201.1151.1008)
Operating System	Windows 10 Education, 64-bit

Coordinate Systems

Image Coordinate System	WGS 84 (EGM96 Geoid)
Output Coordinate System	WGS 84 / UTM zone 32N (EGM96 Geoid)

Processing Options

Detected Template	3D Models
Keypoints Image Scale	Full, Image Scale: 1
Advanced: Matching Image Pairs	Free Flight or Terrestrial
Advanced: Matching Strategy	Use Geometrically Verified Matching: no
Advanced: Keypoint Extraction	Targeted Number of Keypoints: Automatic
Advanced: Calibration	Calibration Method: Standard Internal Parameters Optimization: All External Parameters Optimization: All Rematch: Auto, yes

Point Cloud Densification details

Processing Options

Image Scale	multiscale, 1/2 (Half image size, Default)
Point Density	Optimal
Minimum Number of Matches	3
3D Textured Mesh Generation	yes
3D Textured Mesh Settings:	Resolution: Medium Resolution (default) Color Balancing: no
LOD	Generated: no
Advanced: 3D Textured Mesh Settings	Sample Density Divider: 1
Advanced: Image Groups	group1
Advanced: Use Processing Area	yes
Advanced: Use Annotations	yes

Results

Number of Generated Tiles	1
Number of 3D Densified Points	17235083
Average Density (per m^3)	492.59

DSM, Orthomosaic and Index Details

Processing Options

DSM and Orthomosaic Resolution	1 x GSD (2.16 [cm/pixel])
DSM Filters	Noise Filtering: yes Surface Smoothing: yes, Type: Sharp
Raster DSM	Generated: yes Method: Inverse Distance Weighting Merge Tiles: yes
Orthomosaic	Generated: yes Merge Tiles: yes GeoTIFF Without Transparency: no Google Maps Tiles and KML: no

Appendix C – Quality report from winter survey at Flatstøl

Quality Report

Generated with Pix4Dmapper version 4.3.33

Important: Click on the different icons for:

Help to analyze the results in the Quality Report

Additional information about the sections

Click here for additional tips to analyze the Quality Report

Summary

Project	Flatstolvar
Processed	2019-05-07 13:02:44
Camera Model Name(s)	FC330_3.6_4000x3000 (RGB)
Average Ground Sampling Distance (GSD)	2.15 cm / 0.85 in

Quality Check

Images	median of 23277 keypoints per image	
Dataset	226 out of 226 images calibrated (100%), all images enabled	
Camera Optimization	3.52% relative difference between initial and optimized internal camera parameters	
Matching	median of 10468.6 matches per calibrated image	
Georeferencing	yes, no 3D GCP	

Calibration Details

Number of Calibrated Images	226 out of 226
Number of Geolocated Images	226 out of 226

Initial Image Positions

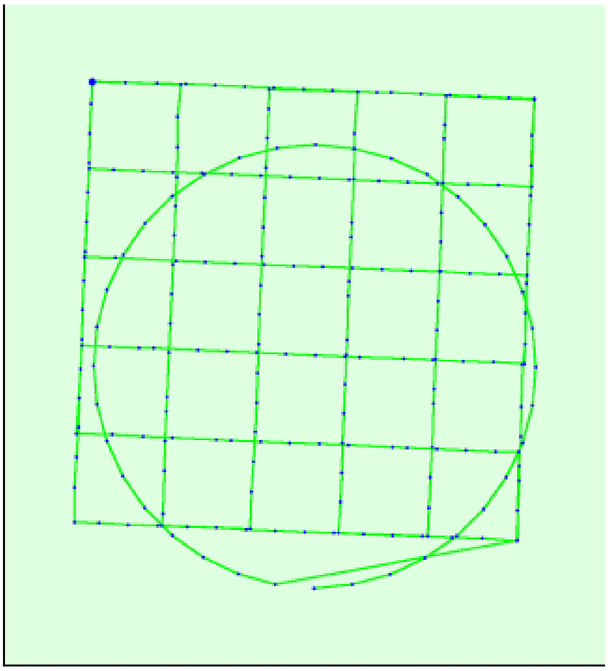
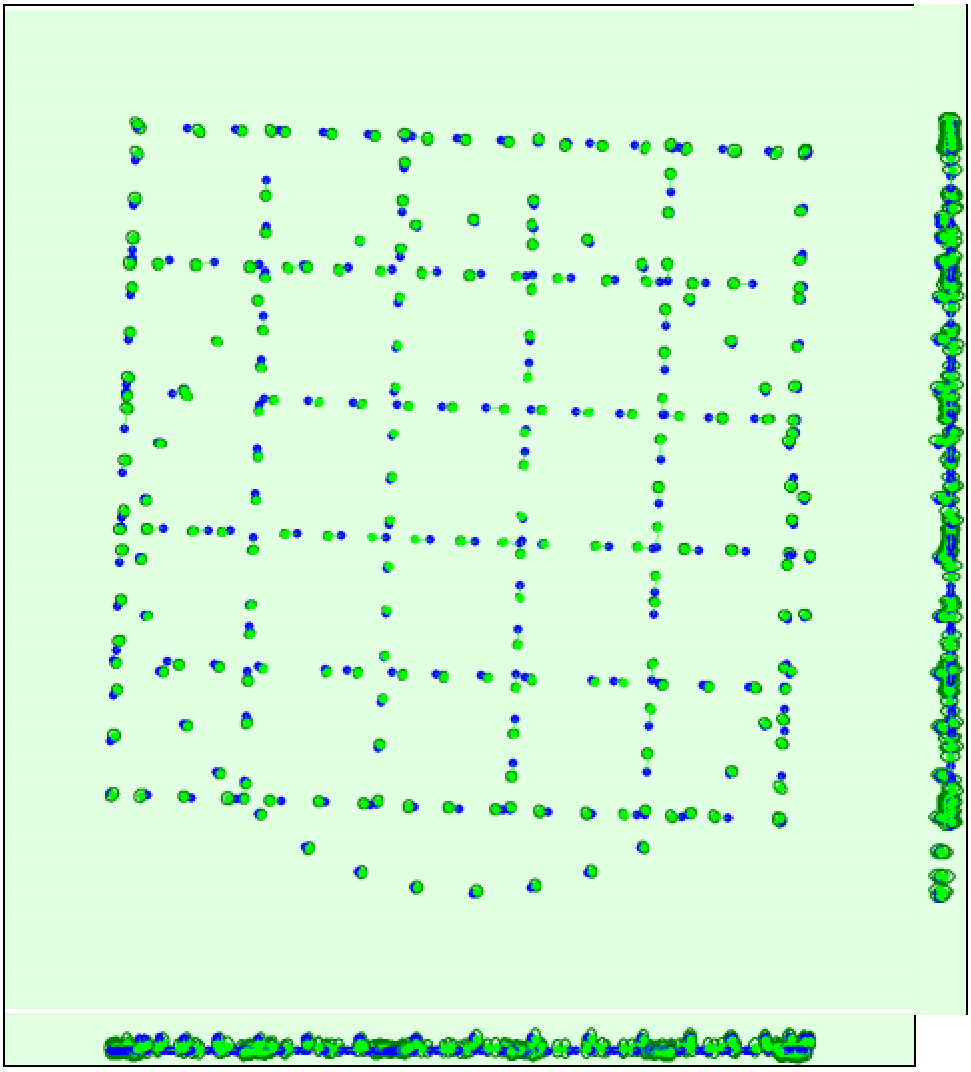


Figure 2: Top view of the initial image position. The green line follows the position of the images in time starting from the large blue dot.

Computed Image/GCPs/Manual Tie Points Positions



Uncertainty ellipses 10x magnified

Figure 3: Offset between initial (blue dots) and computed (green dots) image positions as well as the offset between the GCPs initial positions (blue crosses) and their computed positions (green crosses) in the top-view (XY plane), front-view (XZ plane), and side-view (YZ plane). Dark green ellipses indicate the absolute position uncertainty of the bundle block adjustment result.

Absolute camera position and orientation uncertainties

	X [m]	Y [m]	Z [m]	Omega [degree]	Phi [degree]	Kappa [degree]
Mean	0.147	0.147	0.247	0.078	0.077	0.074
Sigma	0.020	0.020	0.017	0.013	0.007	0.025

Bundle Block Adjustment Details

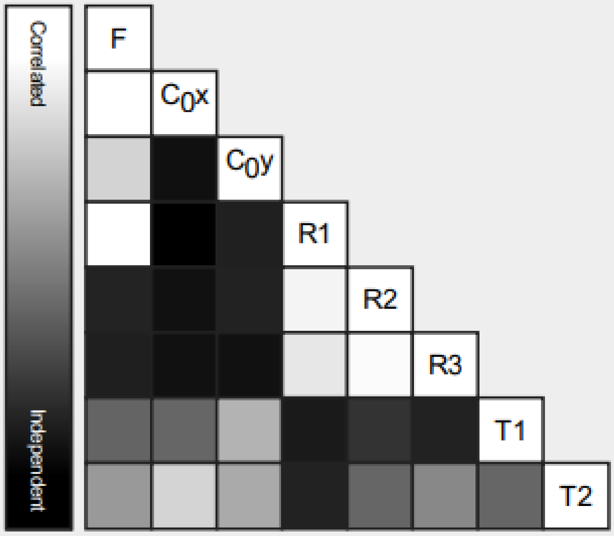
Number of 2D Keypoint Observations for Bundle Block Adjustment	2622678
Number of 3D Points for Bundle Block Adjustment	858499
Mean Reprojection Error [pixels]	0.226

Internal Camera Parameters

FC330_3.6_4000x3000 (RGB). Sensor Dimensions: 6.317 [mm] x 4.738 [mm]

EXIF ID: FC330_3.6_4000x3000

	Focal Length	Principal Point x	Principal Point y	R1	R2	R3	T1	T2
Initial Values	2285.722 [pixel] 3.610 [mm]	2000.006 [pixel] 3.159 [mm]	1500.003 [pixel] 2.369 [mm]	-0.001	-0.002	0.000	-0.001	-0.001
Optimized Values	2366.381 [pixel] 3.737 [mm]	2069.173 [pixel] 3.268 [mm]	1515.435 [pixel] 2.393 [mm]	-0.003	-0.003	0.002	0.000	0.001
Uncertainties (Sigma)	0.146 [pixel] 0.000 [mm]	0.048 [pixel] 0.000 [mm]	0.094 [pixel] 0.000 [mm]	0.000	0.000	0.000	0.000	0.000



The correlation between camera internal parameters determined by the bundle adjustment. White indicates a full correlation between the parameters, ie. any change in one can be fully compensated by the other. Black indicates that the parameter is completely independent, and is not affected by other parameters.

The number of Automatic Tie Points (ATPs) per pixel, averaged over all images of the camera model, is color coded between black and white. White indicates that, on average, more than 16 ATPs have been extracted at the pixel location. Black indicates that, on average, 0 ATPs have been extracted at the pixel location. Click on the image to the see the average direction and magnitude of the re-projection error for each pixel. Note that the vectors are scaled for better visualization. The scale bar indicates the magnitude of 1 pixel error.

2D Keypoints Table

	Number of 2D Keypoints per Image	Number of Matched 2D Keypoints per Image
Median	23277	10469
Min	20007	5984
Max	42619	23857
Mean	24887	11605

3D Points from 2D Keypoint Matches

	Number of 3D Points Observed
In 2 Images	513109
In 3 Images	156260
In 4 Images	71905
In 5 Images	40306
In 6 Images	24306
In 7 Images	16204
In 8 Images	10804
In 9 Images	7540
In 10 Images	5318
In 11 Images	3539
In 12 Images	2563
In 13 Images	1940
In 14 Images	1354
In 15 Images	983
In 16 Images	734
In 17 Images	482
In 18 Images	376
In 19 Images	252
In 20 Images	152
In 21 Images	104
In 22 Images	94
In 23 Images	46
In 24 Images	41
In 25 Images	30
In 26 Images	16
In 27 Images	18
In 28 Images	2
In 29 Images	5
In 30 Images	8
In 31 Images	1
In 32 Images	3
In 33 Images	3
In 41 Images	1

2D Keypoint Matches

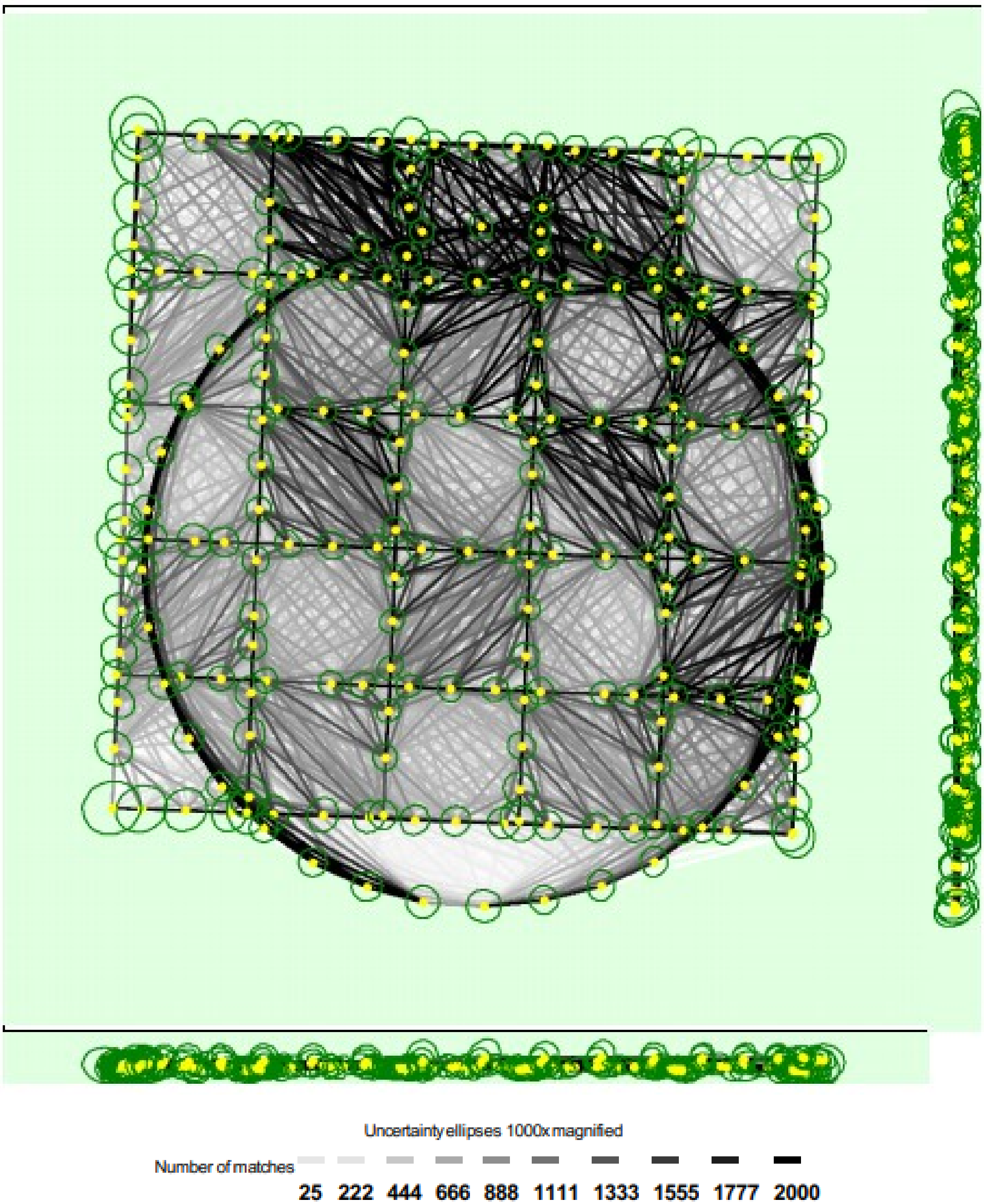


Figure 5: Computed image positions with links between matched images. The darkness of the links indicates the number of matched 2D keypoints between the images. Bright links indicate weak links and require manual tie points or more images. Dark green ellipses indicate the relative camera position uncertainty of the bundle block adjustment result.

Relative camera position and orientation uncertainties

	X[m]	Y[m]	Z[m]	Omega [degree]	Phi [degree]	Kappa [degree]
Mean	0.004	0.004	0.003	0.005	0.005	0.003
Sigma	0.001	0.001	0.001	0.001	0.002	0.001

Geolocation Details

Absolute Geolocation Variance

Min Error [m]	Max Error [m]	Geolocation Error X [%]	Geolocation Error Y [%]	Geolocation Error Z [%]
-	-15.00	0.00	0.00	0.00
-15.00	-12.00	0.00	0.00	0.00
-12.00	-9.00	0.00	0.00	0.00
-9.00	-6.00	0.00	0.00	0.00
-6.00	-3.00	7.96	7.96	0.00
-3.00	0.00	47.79	39.38	53.98
0.00	3.00	33.19	45.58	46.02
3.00	6.00	11.06	7.08	0.00
6.00	9.00	0.00	0.00	0.00
9.00	12.00	0.00	0.00	0.00
12.00	15.00	0.00	0.00	0.00
15.00	-	0.00	0.00	0.00
Mean [m]		0.000005	-0.000001	-0.000002
Sigma [m]		1.962132	1.880805	0.678387
RMS Error [m]		1.962132	1.880805	0.678387

Min Error and Max Error represent geolocation error intervals between -1.5 and 1.5 times the maximum accuracy of all the images. Columns X, Y, Z show the percentage of images with geolocation errors within the predefined error intervals. The geolocation error is the difference between the initial and computed image positions. Note that the image geolocation errors do not correspond to the accuracy of the observed 3D points.

Relative Geolocation Variance

Relative Geolocation Error	Images X [%]	Images Y [%]	Images Z [%]
[-1.00, 1.00]	98.67	97.79	100.00
[-2.00, 2.00]	100.00	100.00	100.00
[-3.00, 3.00]	100.00	100.00	100.00
Mean of Geolocation Accuracy [m]	5.000000	5.000000	10.000000
Sigma of Geolocation Accuracy [m]	0.000000	0.000000	0.000000

Images X, Y, Z represent the percentage of images with a relative geolocation error in X, Y, Z.

Geolocation Orientational Variance	RMS [degree]
Omega	3.817
Phi	3.882
Kappa	7.400

Geolocation RMS error of the orientation angles given by the difference between the initial and computed image orientation angles.

Initial Processing Details

System Information

Hardware	CPU: Intel(R) Core(TM) i7-2600 CPU @ 3.40GHz RAM: 8GB GPU: AMD Radeon HD 5450 (Driver: 15.201.1151.1008)
Operating System	Windows 10 Education, 64-bit

Coordinate Systems

Image Coordinate System	WGS 84 (EGM96 Geoid)
Output Coordinate System	WGS 84 / UTM zone 32N (EGM96 Geoid)

Processing Options

Detected Template	3D Models
Keypoints Image Scale	Full, Image Scale: 1
Advanced: Matching Image Pairs	Free Flight or Terrestrial
Advanced: Matching Strategy	Use Geometrically Verified Matching: no
Advanced: Keypoint Extraction	Targeted Number of Keypoints: Automatic
Advanced: Calibration	Calibration Method: Standard Internal Parameters Optimization: All External Parameters Optimization: All Rematch: Auto, yes

Point Cloud Densification details

Processing Options

Image Scale	multiscale, 1/2 (Half image size, Default)
Point Density	Optimal
Minimum Number of Matches	3
3D Textured Mesh Generation	yes
3D Textured Mesh Settings:	Resolution: Medium Resolution (default) Color Balancing: no
LOD	Generated: no
Advanced: 3D Textured Mesh Settings	Sample Density Divider: 1
Advanced: Image Groups	group1
Advanced: Use Processing Area	yes
Advanced: Use Annotations	yes

Results

Number of Generated Tiles	1
Number of 3D Densified Points	14862823
Average Density (per m^3)	388.89

DSM, Orthomosaic and Index Details

Processing Options

DSM and Orthomosaic Resolution	1 x GSD (2.15 [cm/pixel])
DSM Filters	Noise Filtering: yes Surface Smoothing: yes, Type: Sharp
Raster DSM	Generated: yes Method: Inverse Distance Weighting Merge Tiles: yes
Orthomosaic	Generated: yes Merge Tiles: yes GeoTIFF Without Transparency: no Google Maps Tiles and KML: no

Appendix D – Quality report from summer survey at Tjørhom

Quality Report

Generated with Pix4Dmapper version 4.3.27

Important: Click on the different icons for:

Help to analyze the results in the Quality Report

Additional information about the sections

Click here for additional tips to analyze the Quality Report

Summary

Project	Tjorhomprosjekt
Processed	2018-10-10 15:40:13
Camera Model Name(s)	FC330_3.6_4000x3000 (RGB)
Average Ground Sampling Distance (GSD)	1.77 cm / 0.70 in
Time for Initial Processing (without report)	06h:03m:59s

Quality Check

Images	median of 69828 keypoints per image	
Dataset	161 out of 161 images calibrated (100%), all images enabled	
Camera Optimization	4.33% relative difference between initial and optimized internal camera parameters	
Matching	median of 28402.1 matches per calibrated image	
Georeferencing	yes, no 3D GCP	

Calibration Details

Number of Calibrated Images	161 out of 161
Number of Geolocated Images	161 out of 161

Initial Image Positions

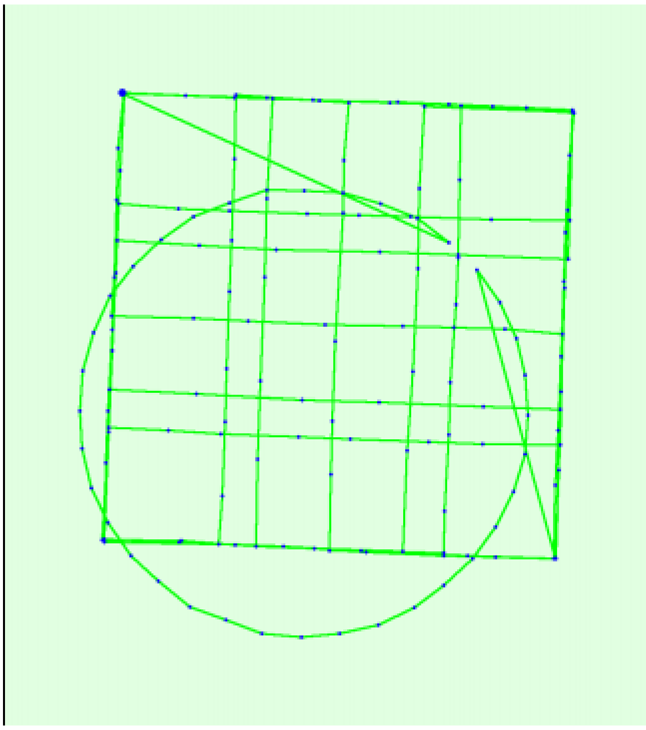
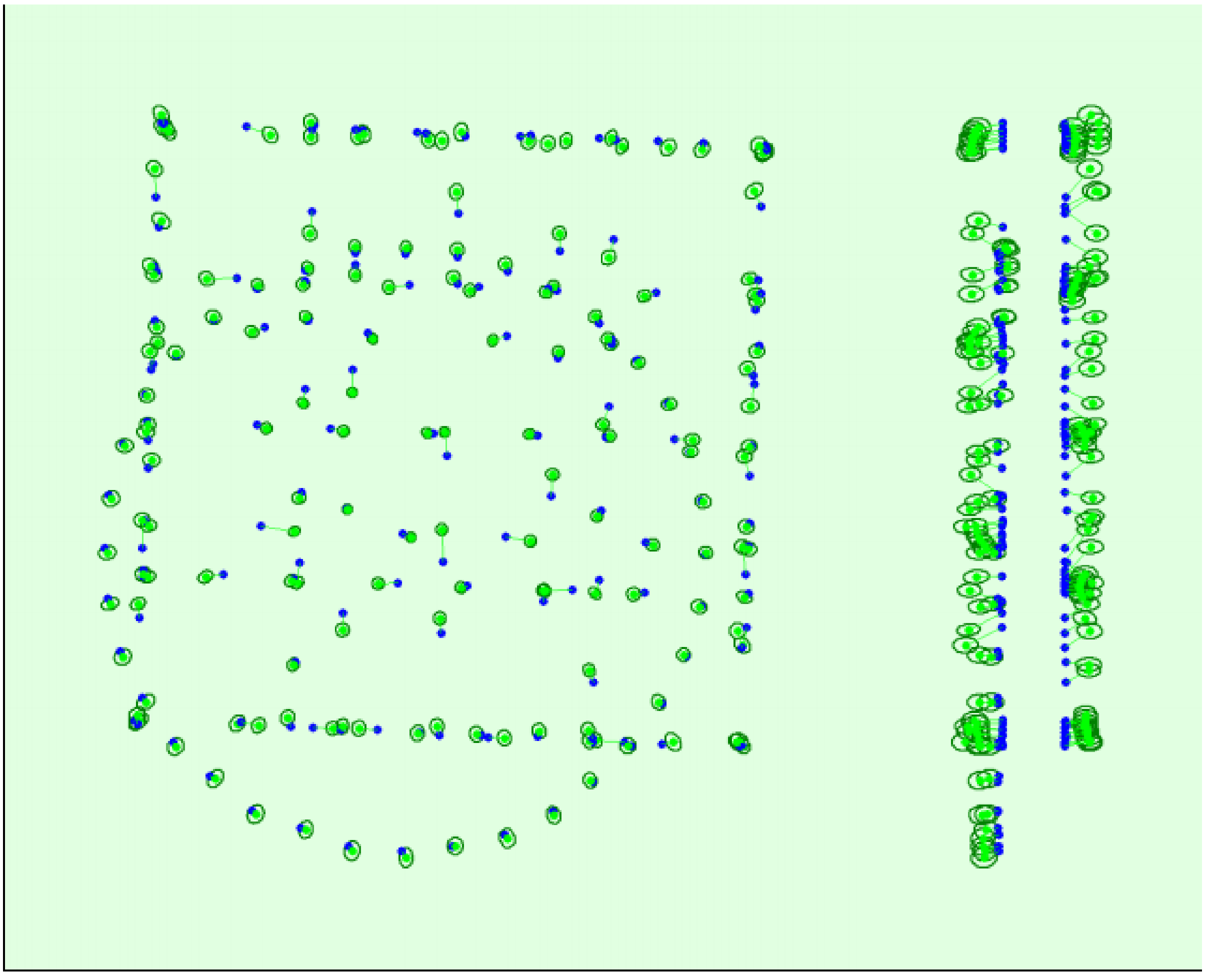
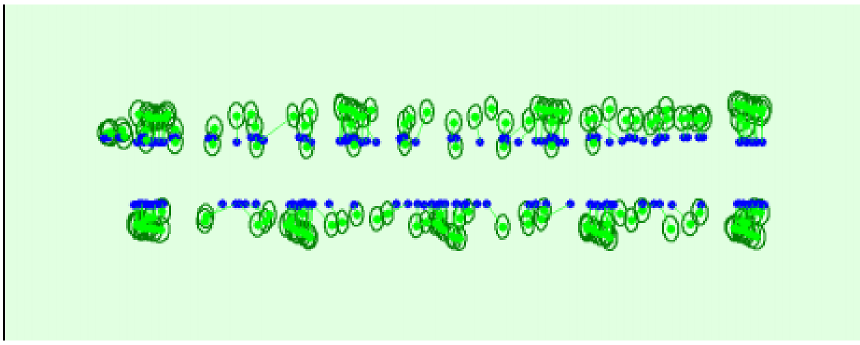


Figure 2: Top view of the initial image position. The green line follows the position of the images in time starting from the large blue dot.

Computed Image/GCPs/Manual Tie Points Positions





Uncertainty ellipses 10x magnified

Figure 3: Offset between initial (blue dots) and computed (green dots) image positions as well as the offset between the GCPs initial positions (blue crosses) and their computed positions (green crosses) in the top-view (XY plane), front-view (XZ plane), and side-view (YZ plane). Dark green ellipses indicate the absolute position uncertainty of the bundle block adjustment result.

Absolute camera position and orientation uncertainties

	X[m]	Y[m]	Z[m]	Omega [degree]	Phi [degree]	Kappa [degree]
Mean	0.110	0.111	0.178	0.063	0.066	0.076
Sigma	0.014	0.015	0.004	0.006	0.004	0.010

Bundle Block Adjustment Details

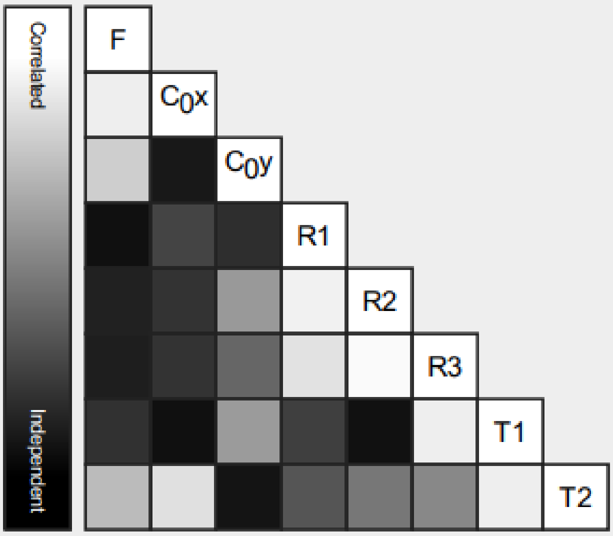
Number of 2D Keypoint Observations for Bundle Block Adjustment	4513918
Number of 3D Points for Bundle Block Adjustment	1702156
Mean Reprojection Error [pixels]	0.204

Internal Camera Parameters

FC330_3.6_4000x3000 (RGB). Sensor Dimensions: 6.317 [mm] x 4.738 [mm]

EXIF ID: FC330_3.6_4000x3000

	Focal Length	Principal Point x	Principal Point y	R1	R2	R3	T1	T2
Initial Values	2285.722 [pixel] 3.610 [mm]	2000.006 [pixel] 3.159 [mm]	1500.003 [pixel] 2.369 [mm]	-0.001	-0.002	0.000	-0.001	-0.001
Optimized Values	2384.875 [pixel] 3.767 [mm]	2071.557 [pixel] 3.272 [mm]	1510.904 [pixel] 2.386 [mm]	-0.004	-0.002	0.002	0.000	0.001
Uncertainties (Sigma)	0.120 [pixel] 0.000 [mm]	0.049 [pixel] 0.000 [mm]	0.088 [pixel] 0.000 [mm]	0.000	0.000	0.000	0.000	0.000



The correlation between camera internal parameters determined by the bundle adjustment. White indicates a full correlation between the parameters, ie. any change in one can be fully compensated by the other. Black indicates that the parameter is completely independent, and is not affected by other parameters.

The number of Automatic Tie Points (ATPs) per pixel, averaged over all images of the camera model, is color coded between black and white. White indicates that, on average, more than 16 ATPs have been extracted at the pixel location. Black indicates that, on average, 0 ATPs have been extracted at the pixel location. Click on the image to the see the average direction and magnitude of the re-projection error for each pixel. Note that the vectors are scaled for better visualization. The scale bar indicates the magnitude of 1 pixel error.

2D Keypoints Table

	Number of 2D Keypoints per Image	Number of Matched 2D Keypoints per Image
Median	69828	28402
Min	53001	11906
Max	79782	41161
Mean	69009	28037

3D Points from 2D Keypoint Matches

	Number of 3D Points Observed
In 2 Images	1177963
In 3 Images	287975
In 4 Images	110090
In 5 Images	51828
In 6 Images	27914
In 7 Images	16115
In 8 Images	9947
In 9 Images	6322
In 10 Images	4125
In 11 Images	2820
In 12 Images	1924
In 13 Images	1362
In 14 Images	979
In 15 Images	669
In 16 Images	491
In 17 Images	399
In 18 Images	266
In 19 Images	215
In 20 Images	178
In 21 Images	135
In 22 Images	87
In 23 Images	79
In 24 Images	74
In 25 Images	42
In 26 Images	47
In 27 Images	27
In 28 Images	20
In 29 Images	17
In 30 Images	10
In 31 Images	11
In 32 Images	5
In 33 Images	2
In 34 Images	5
In 35 Images	3
In 36 Images	3
In 37 Images	2
In 38 Images	1
In 40 Images	1
In 41 Images	2
In 47 Images	1

2D Keypoint Matches

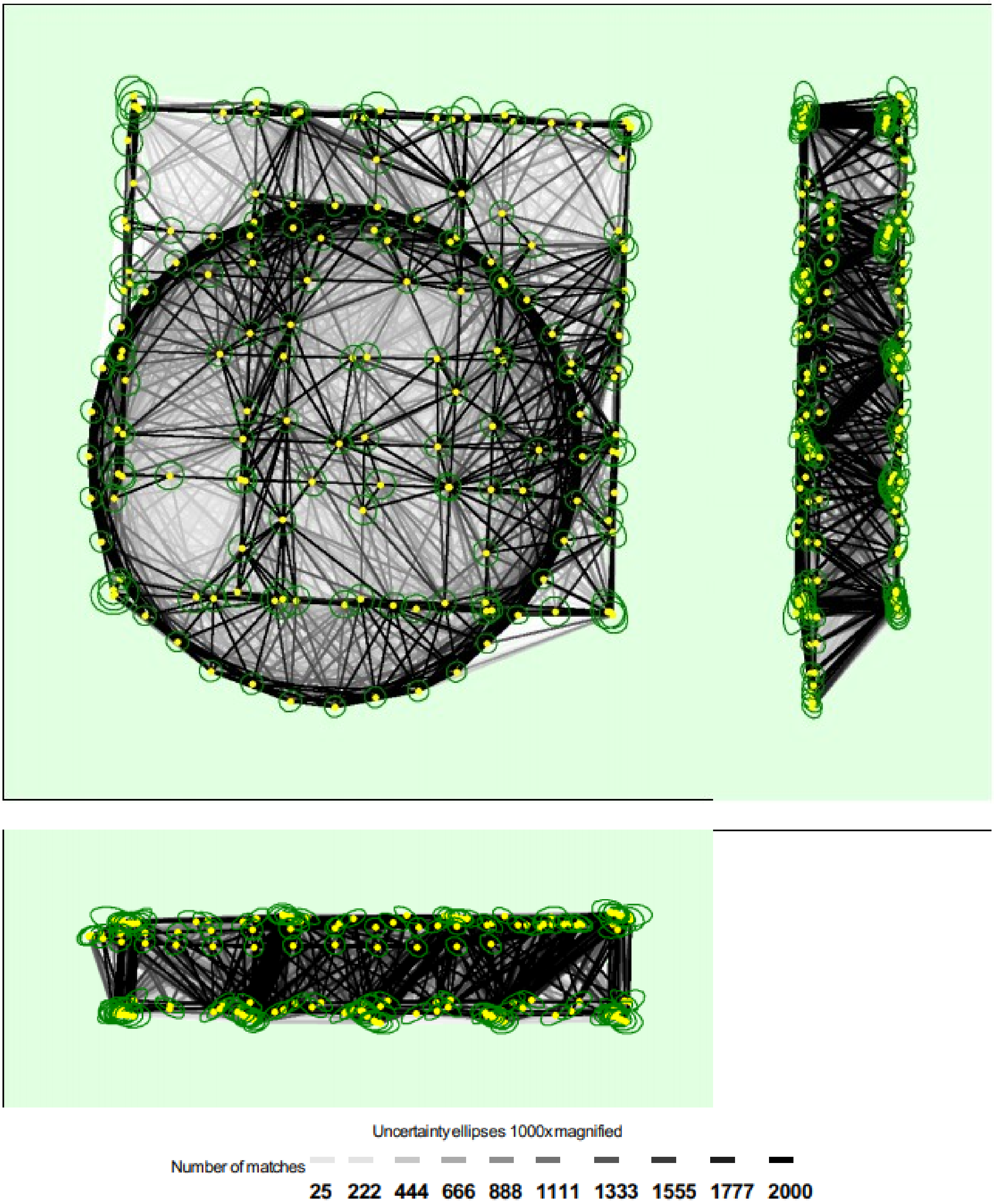


Figure 5: Computed image positions with links between matched images. The darkness of the links indicates the number of matched 2D keypoints between the images. Bright links indicate weak links and require manual tie points or more images. Dark green ellipses indicate the relative camera position uncertainty of the bundle block adjustment result.

Relative camera position and orientation uncertainties

	X [m]	Y [m]	Z [m]	Omega [degree]	Phi [degree]	Kappa [degree]
Mean	0.002	0.002	0.002	0.004	0.003	0.002
Sigma	0.000	0.000	0.000	0.001	0.001	0.001

Geolocation Details

Absolute Geolocation Variance

Min Error [m]	Max Error [m]	Geolocation Error X [%]	Geolocation Error Y [%]	Geolocation Error Z [%]
-	-15.00	0.00	0.00	0.00
-15.00	-12.00	0.00	0.00	0.00
-12.00	-9.00	0.00	0.00	0.00
-9.00	-6.00	0.00	0.00	0.00
-6.00	-3.00	3.73	5.59	27.33
-3.00	0.00	41.61	32.30	17.39
0.00	3.00	52.17	59.63	27.33
3.00	6.00	2.48	2.48	27.95
6.00	9.00	0.00	0.00	0.00
9.00	12.00	0.00	0.00	0.00
12.00	15.00	0.00	0.00	0.00
15.00	-	0.00	0.00	0.00
Mean [m]		0.000001	0.000000	0.000006
Sigma [m]		1.289894	1.452885	3.396327
RMS Error [m]		1.289894	1.452885	3.396327

Min Error and Max Error represent geolocation error intervals between -1.5 and 1.5 times the maximum accuracy of all the images. Columns X, Y, Z show the percentage of images with geolocation errors within the predefined error intervals. The geolocation error is the difference between the initial and computed image positions. Note that the image geolocation errors do not correspond to the accuracy of the observed 3D points.

Relative Geolocation Variance

Relative Geolocation Error	Images X [%]	Images Y [%]	Images Z [%]
[-1.00, 1.00]	99.38	100.00	100.00
[-2.00, 2.00]	100.00	100.00	100.00
[-3.00, 3.00]	100.00	100.00	100.00
Mean of Geolocation Accuracy [m]	5.000000	5.000000	10.000000
Sigma of Geolocation Accuracy [m]	0.000000	0.000000	0.000000

Images X, Y, Z represent the percentage of images with a relative geolocation error in X, Y, Z.

Geolocation Orientational Variance	RMS [degree]
Omega	1.995
Phi	3.496
Kappa	6.213

Geolocation RMS error of the orientation angles given by the difference between the initial and computed image orientation angles.

Initial Processing Details

System Information

Hardware	CPU: Intel(R) Core(TM) i7-2600 CPU @ 3.40GHz RAM: 8GB GPU: AMD Radeon HD 5450 (Driver: 15.201.1151.1008)
Operating System	Windows 10 Education, 64-bit

Coordinate Systems

Image Coordinate System	WGS 84 (EGM96 Geoid)
Output Coordinate System	WGS 84 / UTM zone 32N (EGM96 Geoid)

Processing Options

Detected Template	3D Models
Keypoints Image Scale	Full, Image Scale: 1
Advanced: Matching Image Pairs	Free Flight or Terrestrial
Advanced: Matching Strategy	Use Geometrically Verified Matching: no
Advanced: Keypoint Extraction	Targeted Number of Keypoints: Automatic
Advanced: Calibration	Calibration Method: Standard Internal Parameters Optimization: All External Parameters Optimization: All Rematch: Auto, yes

Point Cloud Densification details

Processing Options

Image Scale	multiscale, 1/2 (Half image size, Default)
Point Density	Optimal
Minimum Number of Matches	3
3D Textured Mesh Generation	yes
3D Textured Mesh Settings:	Resolution: Medium Resolution (default) Color Balancing: no
LOD	Generated: no
Advanced: 3D Textured Mesh Settings	Sample Density Divider: 1
Advanced: Image Groups	group1
Advanced: Use Processing Area	yes
Advanced: Use Annotations	yes
Time for Point Cloud Densification	41m:56s

Time for Point Cloud Classification	NA
Time for 3D Textured Mesh Generation	06m:21s

Results

Number of Generated Tiles	1
Number of 3D Densified Points	11906018
Average Density (per m^3)	894.17

DSM, Orthomosaic and Index Details

Processing Options

DSM and Orthomosaic Resolution	1 x GSD (1.77 [cm/pixel])
DSM Filters	Noise Filtering: yes Surface Smoothing: yes, Type: Sharp
Raster DSM	Generated: yes Method: Inverse Distance Weighting Merge Tiles: yes
Orthomosaic	Generated: yes Merge Tiles: yes GeoTIFF Without Transparency: no Google Maps Tiles and KML: no
Time for DSM Generation	11m:05s
Time for Orthomosaic Generation	43m:43s
Time for DTM Generation	00s
Time for Contour Lines Generation	00s
Time for Reflectance Map Generation	00s
Time for Index Map Generation	00s

Appendix E – Quality report from winter survey at Tjørhom

Quality Report

Generated with Pix4Dmapper version 4.3.33

Important: Click on the different icons for:

Help to analyze the results in the Quality Report

Additional information about the sections

Click here for additional tips to analyze the Quality Report

Summary

Project	Tjorhomvar
Processed	2019-05-07 13:17:45
Camera Model Name(s)	L1D-20c_10.3_5472x3648 (RGB)
Average Ground Sampling Distance (GSD)	0.11 cm / 0.04 in

Quality Check

Images	median of 83463 keypoints per image	
Dataset	204 out of 206 images calibrated (99%), all images enabled, 2 blocks	
Camera Optimization	1.53% relative difference between initial and optimized internal camera parameters	
Matching	median of 16288.8 matches per calibrated image	
Georeferencing	yes, no 3D GCP	

Calibration Details

Number of Calibrated Images	204 out of 206
Number of Geolocated Images	206 out of 206

Initial Image Positions

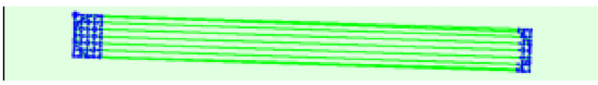


Figure 2: Top view of the initial image position. The green line follows the position of the images in time starting from the large blue dot.

Computed Image/GCPs/Manual Tie Points Positions

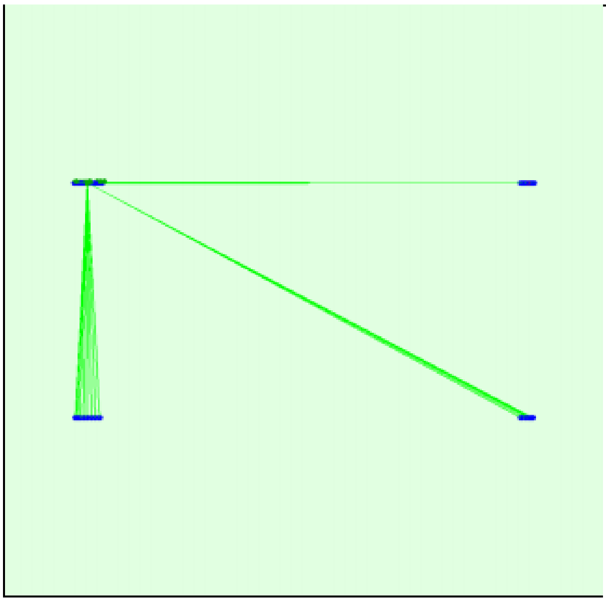


Figure 3: Offset between initial (blue dots) and computed (green dots) image positions as well as the offset between the GCPs initial positions (blue crosses) and their computed positions (green crosses) in the top-view (XY plane), front-view (XZ plane), and side-view (YZ plane). Red dots indicate disabled or uncalibrated images.

Absolute camera position and orientation uncertainties

Uncertainty computation failed.

Bundle Block Adjustment Details

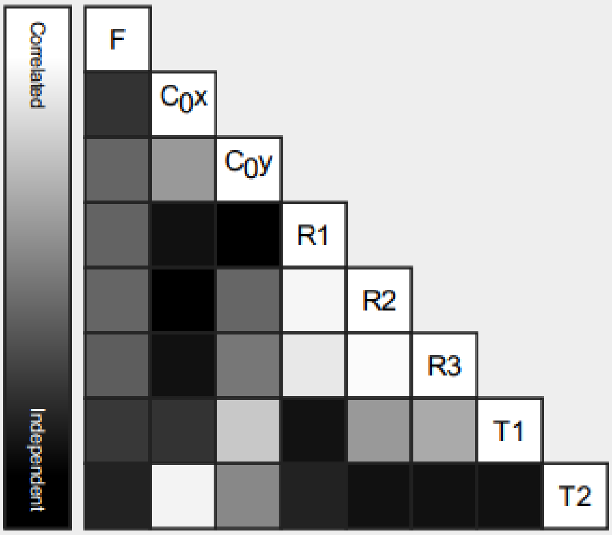
Number of 2D Keypoint Observations for Bundle Block Adjustment	3930683
Number of 3D Points for Bundle Block Adjustment	1695381
Mean Reprojection Error [pixels]	0.444

Internal Camera Parameters

L1D-20c_10.3_5472x3648 (RGB). Sensor Dimensions: 12.825 [mm] x 8.550 [mm]

EXIF ID: L1D-20c_10.3_5472x3648

	Focal Length	Principal Point x	Principal Point y	R1	R2	R3	T1	T2
Initial Values	4470.830 [pixel] 10.479 [mm]	2770.870 [pixel] 6.494 [mm]	1698.700 [pixel] 3.981 [mm]	0.009	0.040	-0.050	-0.003	0.002
Optimized Values	4539.615 [pixel] 10.640 [mm]	2762.691 [pixel] 6.475 [mm]	1635.283 [pixel] 3.833 [mm]	0.018	0.012	-0.026	-0.005	0.002
Uncertainties (Sigma)	0.816 [pixel] 0.002 [mm]	1.028 [pixel] 0.002 [mm]	0.873 [pixel] 0.002 [mm]	0.001	0.005	0.007	0.000	0.000



The correlation between camera internal parameters determined by the bundle adjustment. White indicates a full correlation between the parameters, ie. any change in one can be fully compensated by the other. Black indicates that the parameter is completely independent, and is not affected by other parameters.

The number of Automatic Tie Points (ATPs) per pixel, averaged over all images of the camera model, is color coded between black and white. White indicates that, on average, more than 16 ATPs have been extracted at the pixel location. Black indicates that, on average, 0 ATPs have been extracted at the pixel location. Click on the image to the see the average direction and magnitude of the re-projection error for each pixel. Note that the vectors are scaled for better visualization. The scale bar indicates the magnitude of 1 pixel error.

2D Keypoints Table

	Number of 2D Keypoints per Image	Number of Matched 2D Keypoints per Image
Median	83463	16289
Min	67007	3478
Max	88763	57293
Mean	81675	19268

3D Points from 2D Keypoint Matches

	Number of 3D Points Observed
In 2 Images	1422916
In 3 Images	166303
In 4 Images	48478
In 5 Images	22449
In 6 Images	12453
In 7 Images	7438
In 8 Images	4772
In 9 Images	3495
In 10 Images	2841
In 11 Images	1726
In 12 Images	932
In 13 Images	707
In 14 Images	261
In 15 Images	121
In 16 Images	85
In 17 Images	68
In 18 Images	48
In 19 Images	44
In 20 Images	47
In 21 Images	29
In 22 Images	31
In 23 Images	26
In 24 Images	21
In 25 Images	13
In 26 Images	15
In 27 Images	13
In 28 Images	9
In 29 Images	8
In 30 Images	8
In 31 Images	7
In 32 Images	6
In 33 Images	5
In 34 Images	1
In 35 Images	3
In 39 Images	2

2D Keypoint Matches

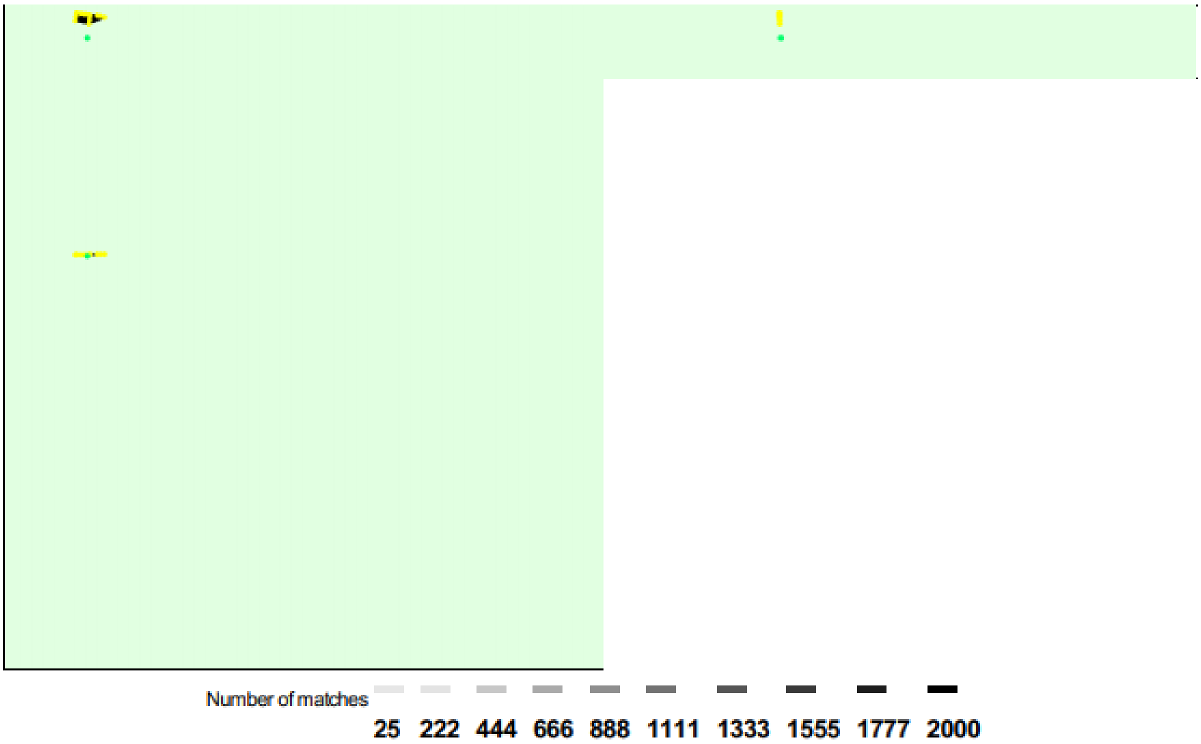


Figure 5: Computed image positions with links between matched images. The darkness of the links indicates the number of matched 2D keypoints between the images. Bright links indicate weak links and require manual tie points or more images.

Geolocation Details

Absolute Geolocation Variance

Min Error [m]	Max Error [m]	Geolocation Error X [%]	Geolocation Error Y [%]	Geolocation Error Z [%]
-	-15.00	30.10	34.95	0.00
-15.00	-12.00	7.77	0.00	0.00
-12.00	-9.00	2.91	2.91	0.00
-9.00	-6.00	1.94	8.74	0.00
-6.00	-3.00	1.94	0.97	0.00
-3.00	0.00	2.91	1.94	37.86
0.00	3.00	8.74	1.94	62.14
3.00	6.00	1.94	0.97	0.00

6.00	9.00	2.91	7.77	0.00
9.00	12.00	0.97	3.88	0.00
12.00	15.00	3.88	0.97	0.00
15.00	-	33.98	34.95	0.00
Mean [m]		0.142913	0.886140	0.030428
Sigma [m]		21.632567	28.630344	0.146336
RMS Error [m]		21.633039	28.644054	0.149466

Min Error and Max Error represent geolocation error intervals between -1.5 and 1.5 times the maximum accuracy of all the images. Columns X, Y, Z show the percentage of images with geolocation errors within the predefined error intervals. The geolocation error is the difference between the initial and computed image positions. Note that the image geolocation errors do not correspond to the accuracy of the observed 3D points.

Relative Geolocation Variance

Relative Geolocation Error	Images X [%]	Images Y [%]	Images Z [%]
[-1.00, 1.00]	15.53	4.85	100.00
[-2.00, 2.00]	20.39	26.21	100.00
[-3.00, 3.00]	35.92	30.10	100.00
Mean of Geolocation Accuracy [m]	5.000000	5.000000	10.000000
Sigma of Geolocation Accuracy [m]	0.000000	0.000000	0.000000

Images X, Y, Z represent the percentage of images with a relative geolocation error in X, Y, Z.

Geolocation Orientational Variance	RMS [degree]
Omega	113.979
Phi	47.054
Kappa	71.465

Geolocation RMS error of the orientation angles given by the difference between the initial and computed image orientation angles.

Initial Processing Details

System Information

Hardware	CPU: Intel(R) Core(TM) i7-2600 CPU @ 3.40GHz RAM: 8GB GPU: AMD Radeon HD 5450 (Driver: 15.201.1151.1008)
Operating System	Windows 10 Education, 64-bit

Coordinate Systems

Image Coordinate System	WGS 84 (EGM96 Geoid)
Output Coordinate System	WGS 84 / UTM zone 32N (EGM96 Geoid)

Processing Options

Detected Template	3D Models
Keypoints Image Scale	Full, Image Scale: 1
Advanced: Matching Image Pairs	Free Flight or Terrestrial
Advanced: Matching Strategy	Use Geometrically Verified Matching: no
Advanced: Keypoint Extraction	Targeted Number of Keypoints: Automatic
Advanced: Calibration	Calibration Method: Standard Internal Parameters Optimization: All External Parameters Optimization: All Rematch: Auto, yes

Point Cloud Densification details

Processing Options

Image Scale	multiscale, 1/2 (Half image size, Default)
Point Density	Optimal
Minimum Number of Matches	3
3D Textured Mesh Generation	yes
3D Textured Mesh Settings:	Resolution: Medium Resolution (default) Color Balancing: no
LOD	Generated: no
Advanced: 3D Textured Mesh Settings	Sample Density Divider: 1
Advanced: Image Groups	group1
Advanced: Use Processing Area	yes
Advanced: Use Annotations	yes

Results

Number of Generated Tiles	1
Number of 3D Densified Points	5555234
Average Density (per m^3)	337655

DSM, Orthomosaic and Index Details

Processing Options

DSM and Orthomosaic Resolution	1 x GSD (0.114 [cm/pixel])
DSM Filters	Noise Filtering: yes Surface Smoothing: yes, Type: Sharp
Raster DSM	Generated: yes Method: Inverse Distance Weighting Merge Tiles: yes
Orthomosaic	Generated: yes Merge Tiles: yes GeoTIFF Without Transparency: no Google Maps Tiles and KML: no

Appendix F – Quality report from 2nd winter survey at Tjørhom

Quality Report

Generated with Pix4Dmapper version 4.3.33

Important: Click on the different icons for:

Help to analyze the results in the Quality Report

Additional information about the sections

Click here for additional tips to analyze the Quality Report

Summary

Project	Tjørhomvarkaspar
Processed	2019-04-01 20:25:10
Camera Model Name(s)	FC330_3.6_4000x3000 (RGB)
Average Ground Sampling Distance (GSD)	2.14 cm / 0.84 in

Quality Check

Images	median of 13826 keypoints per image	
Dataset	39 out of 75 images calibrated (52%), all images enabled	
Camera Optimization	3.63% relative difference between initial and optimized internal camera parameters	
Matching	median of 1252.82 matches per calibrated image	
Georeferencing	yes, no 3D GCP	

Calibration Details

Number of Calibrated Images	39 out of 75
Number of Geolocated Images	75 out of 75

Initial Image Positions

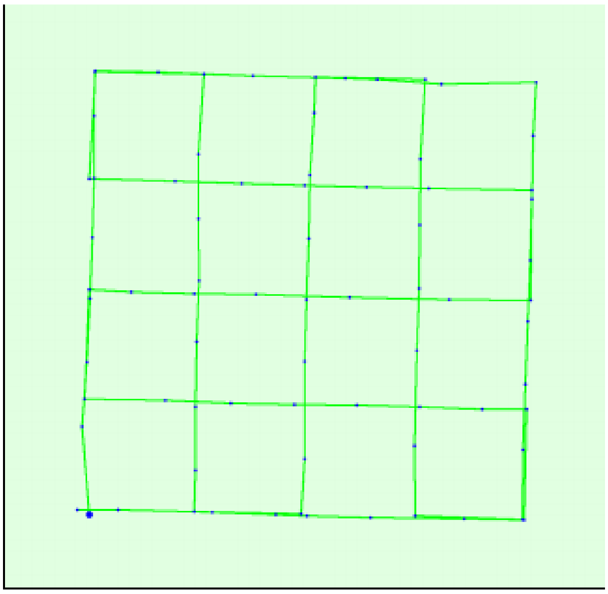


Figure 2: Top view of the initial image position. The green line follows the position of the images in time starting from the large blue dot.

Computed Image/GCPs/Manual Tie Points Positions

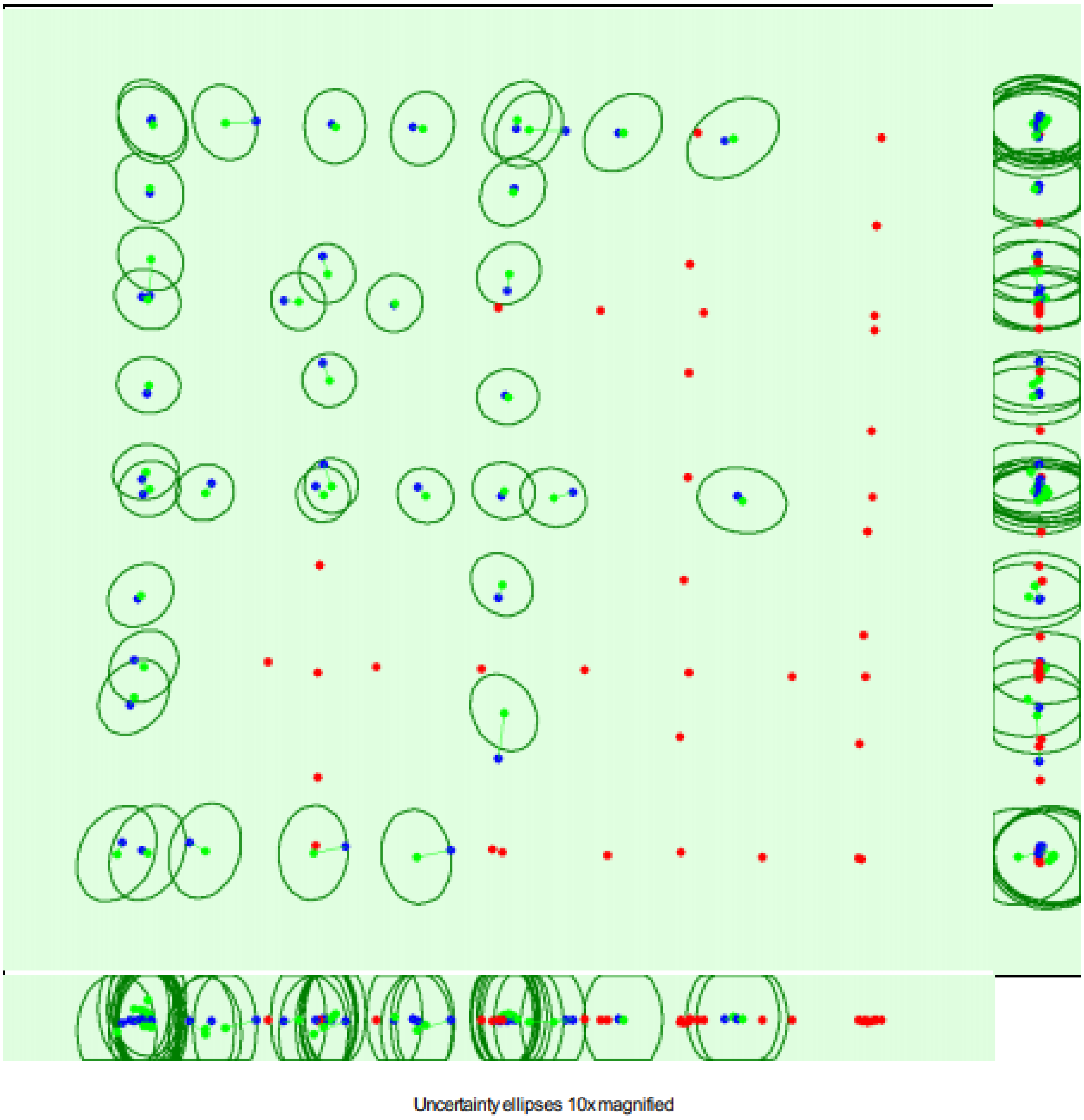


Figure 3: Offset between initial (blue dots) and computed (green dots) image positions as well as the offset between the GCPs initial positions (blue crosses) and their computed positions (green crosses) in the top-view (XY plane), front-view (XZ plane), and side-view (YZ plane). Red dots indicate disabled or uncalibrated images. Dark green ellipses indicate the absolute position uncertainty of the bundle block adjustment result.

Absolute camera position and orientation uncertainties

	X[m]	Y[m]	Z[m]	Omega [degree]	Phi [degree]	Kappa [degree]
Mean	0.416	0.439	0.693	0.226	0.258	0.294
Sigma	0.054	0.082	0.013	0.004	0.003	0.017

Bundle Block Adjustment Details

Number of 2D Keypoint Observations for Bundle Block Adjustment	57604
Number of 3D Points for Bundle Block Adjustment	21573

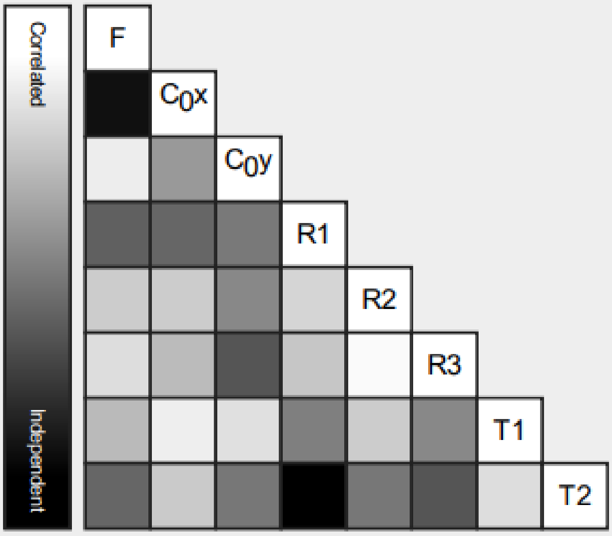
Mean Reprojection Error [pixels]	0.230

Internal Camera Parameters

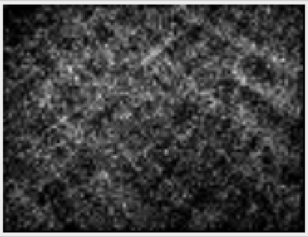
FC330_3.6_4000x3000 (RGB). Sensor Dimensions: 6.317 [mm] x 4.738 [mm]

EXIF ID: FC330_3.6_4000x3000

	Focal Length	Principal Point x	Principal Point y	R1	R2	R3	T1	T2
Initial Values	2285.722 [pixel] 3.610 [mm]	2000.006 [pixel] 3.159 [mm]	1500.003 [pixel] 2.369 [mm]	-0.001	-0.002	0.000	-0.001	-0.001
Optimized Values	2368.881 [pixel] 3.741 [mm]	2057.187 [pixel] 3.249 [mm]	1515.110 [pixel] 2.393 [mm]	-0.003	-0.003	0.001	0.000	0.000
Uncertainties (Sigma)	1.530 [pixel] 0.002 [mm]	0.323 [pixel] 0.001 [mm]	0.973 [pixel] 0.002 [mm]	0.000	0.001	0.001	0.000	0.000



The correlation between camera internal parameters determined by the bundle adjustment. White indicates a full correlation between the parameters, ie. any change in one can be fully compensated by the other. Black indicates that the parameter is completely independent, and is not affected by other parameters.



The number of Automatic Tie Points (ATPs) per pixel, averaged over all images of the camera model, is color coded between black and white. White indicates that, on average, more than 16 ATPs have been extracted at the pixel location. Black indicates that, on average, 0 ATPs have been extracted at the pixel location. Click on the image to the see the average direction and magnitude of the re-projection error for each pixel. Note that the vectors are scaled for better visualization. The scale bar indicates the magnitude of 1 pixel error.

2D Keypoints Table

	Number of 2D Keypoints per Image	Number of Matched 2D Keypoints per Image
Median	13826	1253
Min	11819	169
Max	19251	4027
Mean	14428	1477

3D Points from 2D Keypoint Matches

	Number of 3D Points Observed
In 2 Images	15191
In 3 Images	3199
In 4 Images	1348
In 5 Images	715
In 6 Images	432
In 7 Images	260
In 8 Images	147
In 9 Images	95
In 10 Images	59
In 11 Images	46
In 12 Images	23
In 13 Images	16
In 14 Images	21
In 15 Images	9
In 16 Images	5
In 17 Images	3
In 18 Images	2
In 19 Images	1
In 20 Images	1

2D Keypoint Matches

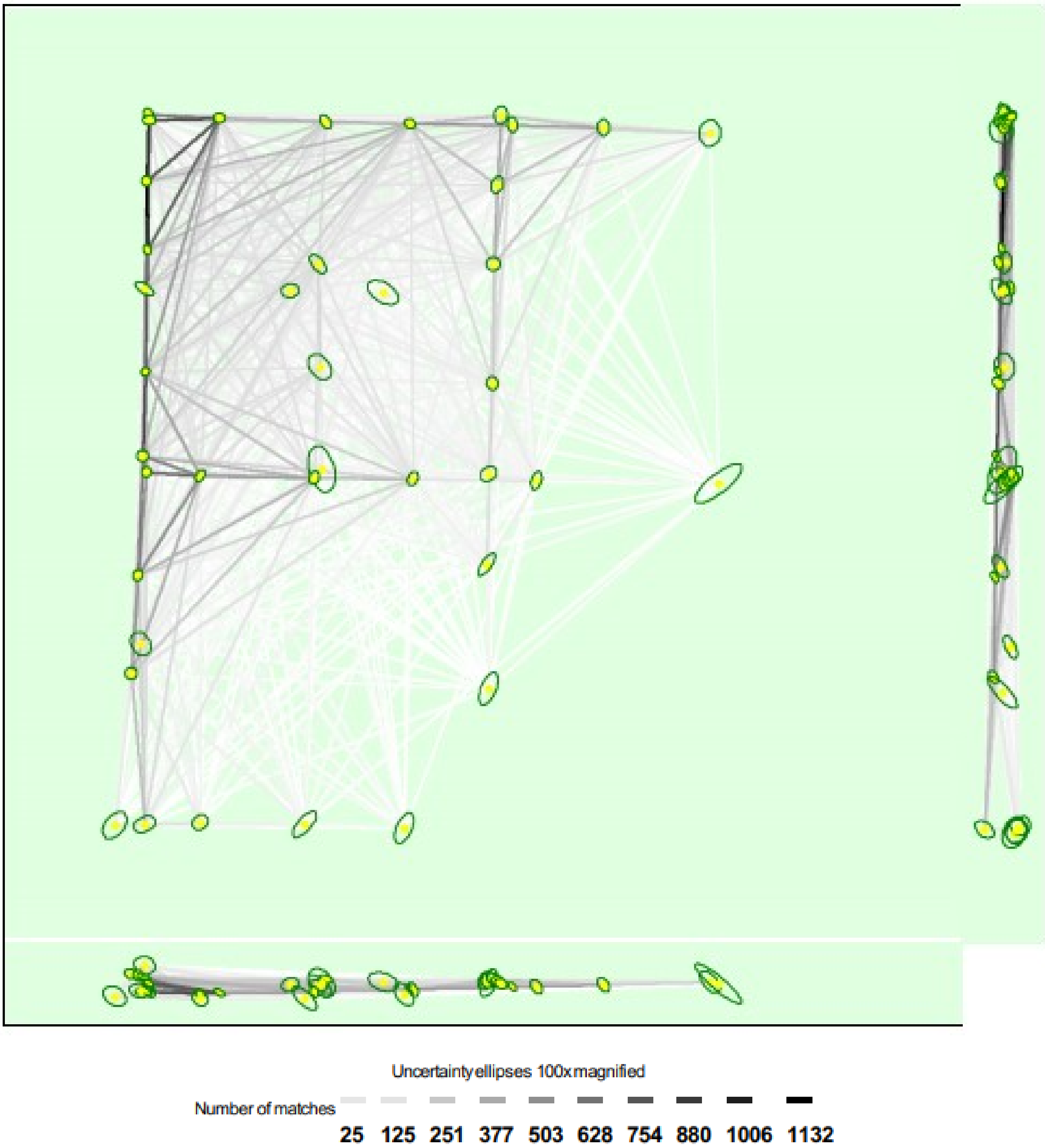


Figure 5: Computed image positions with links between matched images. The darkness of the links indicates the number of matched 2D keypoints between the images. Bright links indicate weak links and require manual tie points or more images. Dark green ellipses indicate the relative camera position uncertainty of the bundle block adjustment result.

Relative camera position and orientation uncertainties

	X[m]	Y[m]	Z[m]	Omega [degree]	Phi [degree]	Kappa [degree]
Mean	0.011	0.012	0.009	0.021	0.020	0.011
Sigma	0.005	0.006	0.005	0.007	0.008	0.003

Geolocation Details

Absolute Geolocation Variance

Min Error [m]	Max Error [m]	Geolocation Error X [%]	Geolocation Error Y [%]	Geolocation Error Z [%]
-	-15.00	0.00	0.00	0.00
-15.00	-12.00	0.00	0.00	0.00
-12.00	-9.00	0.00	0.00	0.00
-9.00	-6.00	0.00	0.00	0.00
-6.00	-3.00	0.00	5.13	0.00
-3.00	0.00	76.92	33.33	53.85
0.00	3.00	12.82	61.54	46.15
3.00	6.00	10.26	0.00	0.00
6.00	9.00	0.00	0.00	0.00
9.00	12.00	0.00	0.00	0.00
12.00	15.00	0.00	0.00	0.00
15.00	-	0.00	0.00	0.00
Mean [m]		-0.000012	0.000001	-0.000018
Sigma [m]		1.574066	1.637446	0.832854
RMS Error [m]		1.574066	1.637446	0.832854

Min Error and Max Error represent geolocation error intervals between -1.5 and 1.5 times the maximum accuracy of all the images. Columns X, Y, Z show the percentage of images with geolocation errors within the predefined error intervals. The geolocation error is the difference between the initial and computed image positions. Note that the image geolocation errors do not correspond to the accuracy of the observed 3D points.

Relative Geolocation Variance

Relative Geolocation Error	Images X [%]	Images Y [%]	Images Z [%]
[-1.00, 1.00]	100.00	97.44	100.00
[-2.00, 2.00]	100.00	100.00	100.00
[-3.00, 3.00]	100.00	100.00	100.00
Mean of Geolocation Accuracy [m]	5.000000	5.000000	10.000000
Sigma of Geolocation Accuracy [m]	0.000000	0.000000	0.000000

Images X, Y, Z represent the percentage of images with a relative geolocation error in X, Y, Z.

Geolocation Orientational Variance	RMS [degree]
Omega	2.494
Phi	1.635
Kappa	8.977

Geolocation RMS error of the orientation angles given by the difference between the initial and computed image orientation angles.

Initial Processing Details

System Information

Hardware	CPU: Intel(R) Core(TM) i7-2600 CPU @ 3.40GHz RAM: 8GB GPU: AMD Radeon HD 5450 (Driver: 15.201.1151.1008)
Operating System	Windows 10 Education, 64-bit

Coordinate Systems

Image Coordinate System	WGS 84 (EGM96 Geoid)
Output Coordinate System	WGS 84 / UTM zone 32N (EGM96 Geoid)

Processing Options

Detected Template	3D Models
Keypoints Image Scale	Full, Image Scale: 1
Advanced: Matching Image Pairs	Free Flight or Terrestrial
Advanced: Matching Strategy	Use Geometrically Verified Matching: no
Advanced: Keypoint Extraction	Targeted Number of Keypoints: Automatic
Advanced: Calibration	Calibration Method: Standard Internal Parameters Optimization: All External Parameters Optimization: All Rematch: Auto, yes

Point Cloud Densification details

Processing Options

Image Scale	multiscale, 1/2 (Half image size, Default)
Point Density	Optimal
Minimum Number of Matches	3
3D Textured Mesh Generation	yes
3D Textured Mesh Settings:	Resolution: Medium Resolution (default) Color Balancing: no
LOD	Generated: no
Advanced: 3D Textured Mesh Settings	Sample Density Divider: 1
Advanced: Image Groups	group1
Advanced: Use Processing Area	yes
Advanced: Use Annotations	yes

Results

Number of Generated Tiles	1
Number of 3D Densified Points	921886
Average Density (per m^3)	276.17

DSM, Orthomosaic and Index Details

Processing Options

DSM and Orthomosaic Resolution	1 x GSD (2.14 [cm/pixel])
DSM Filters	Noise Filtering: yes Surface Smoothing: yes, Type: Sharp
Raster DSM	Generated: yes Method: Inverse Distance Weighting Merge Tiles: yes

Orthomosaic	Generated: yes Merge Tiles: yes GeoTIFF Without Transparency: no Google Maps Tiles and KML: no

Appendix G – Quality report from summer survey at Nesjen

Quality Report

Generated with Pix4Dmapper version 4.3.27

Important: Click on the different icons for:

Help to analyze the results in the Quality Report

Additional information about the sections

Click here for additional tips to analyze the Quality Report

Summary

Project	Nesjen
Processed	2018-10-05 15:20:01
Camera Model Name(s)	FC330_3.6_4000x3000 (RGB)
Average Ground Sampling Distance (GSD)	1.74 cm / 0.68 in
Time for Initial Processing (without report)	02h:26m:43s

Quality Check

Images	median of 54804 keypoints per image	
Dataset	237 out of 237 images calibrated (100%), all images enabled	
Camera Optimization	4.88% relative difference between initial and optimized internal camera parameters	
Matching	median of 23360.1 matches per calibrated image	
Georeferencing	yes, no 3D GCP	

Calibration Details

Number of Calibrated Images	237 out of 237
Number of Geolocated Images	237 out of 237

Initial Image Positions

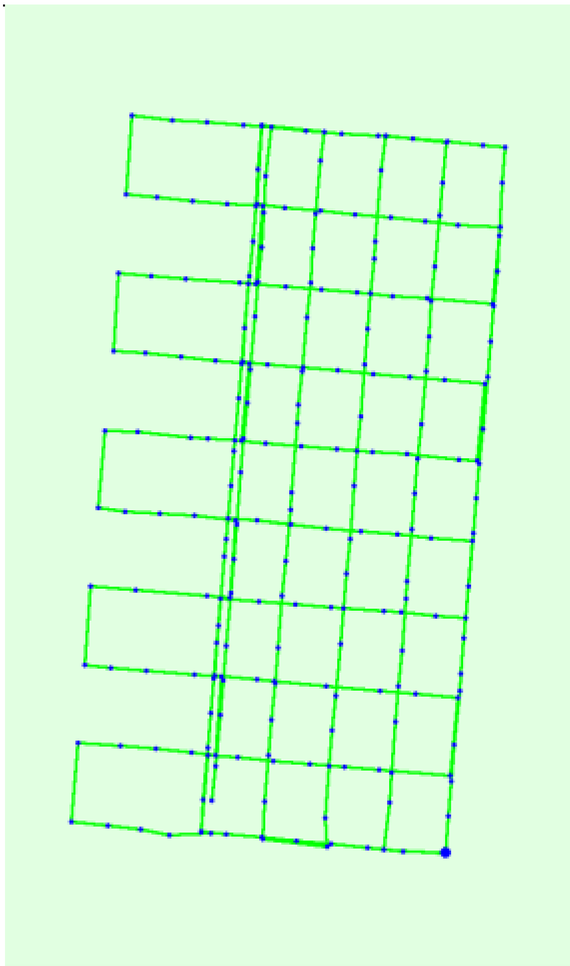
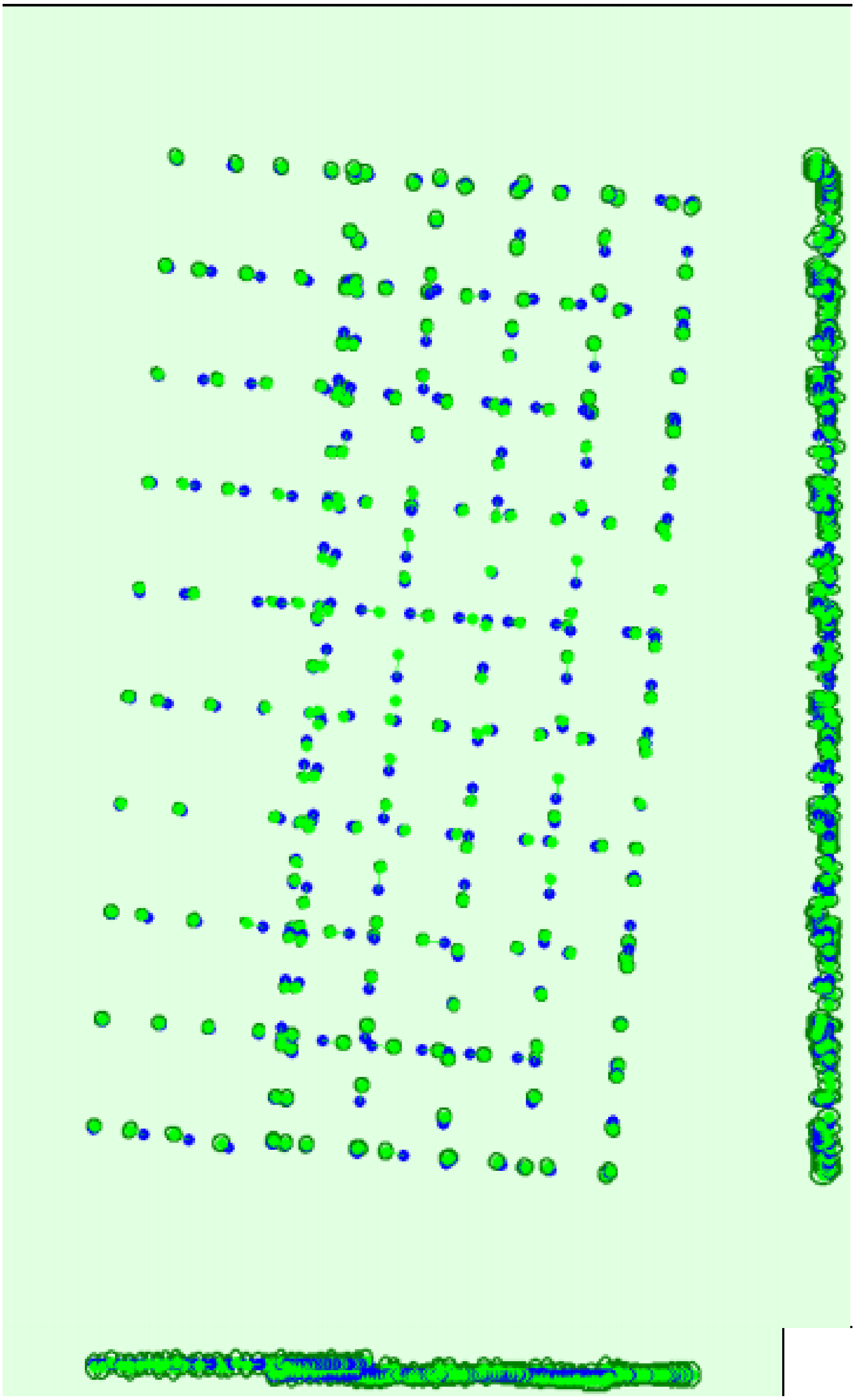


Figure 2: Top view of the initial image position. The green line follows the position of the images in time starting from the large blue dot.

Computed Image/GCPs/Manual Tie Points Positions



Uncertainty ellipses 10x magnified

Figure 3: Offset between initial (blue dots) and computed (green dots) image positions as well as the offset between the GCPs initial positions (blue crosses) and their computed positions (green crosses) in the top-view (XY plane), front-view (XZ plane), and side-view (YZ plane). Dark green ellipses indicate the absolute position uncertainty of the bundle block adjustment result.

Absolute camera position and orientation uncertainties

	X[m]	Y[m]	Z[m]	Omega [degree]	Phi [degree]	Kappa [degree]
Mean	0.171	0.176	0.292	0.084	0.094	0.076
Sigma	0.028	0.033	0.025	0.002	0.003	0.004

Bundle Block Adjustment Details

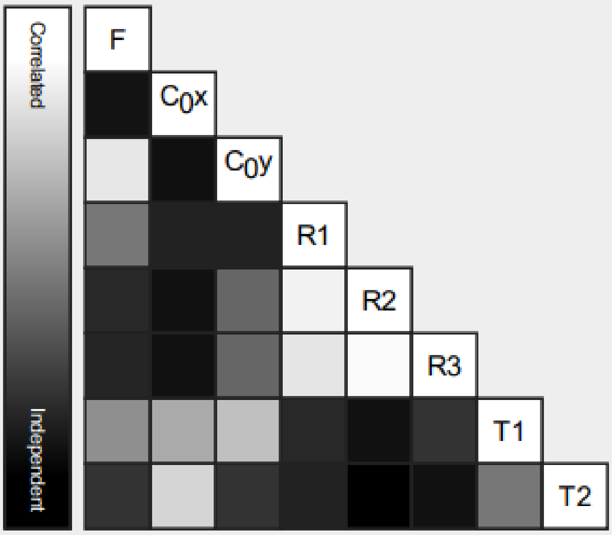
Number of 2D Keypoint Observations for Bundle Block Adjustment	5457875
Number of 3D Points for Bundle Block Adjustment	2054937
Mean Reprojection Error [pixels]	0.228

Internal Camera Parameters

FC330_3.6_4000x3000 (RGB). Sensor Dimensions: 6.317 [mm] x 4.738 [mm]

EXIF ID: FC330_3.6_4000x3000

	Focal Length	Principal Point x	Principal Point y	R1	R2	R3	T1	T2
Initial Values	2285.722 [pixel] 3.610 [mm]	2000.006 [pixel] 3.159 [mm]	1500.003 [pixel] 2.369 [mm]	-0.001	-0.002	0.000	-0.001	-0.001
Optimized Values	2397.314 [pixel] 3.786 [mm]	1973.709 [pixel] 3.117 [mm]	1404.449 [pixel] 2.218 [mm]	0.003	-0.013	0.007	-0.000	0.000
Uncertainties (Sigma)	0.201 [pixel] 0.000 [mm]	0.059 [pixel] 0.000 [mm]	0.134 [pixel] 0.000 [mm]	0.000	0.000	0.000	0.000	0.000



The correlation between camera internal parameters determined by the bundle adjustment. White indicates a full correlation between the parameters, ie. any change in one can be fully compensated by the other. Black indicates that the parameter is completely independent, and is not affected by other parameters.

The number of Automatic Tie Points (ATPs) per pixel, averaged over all images of the camera model, is color coded between black and white. White indicates that, on average, more than 16 ATPs have been extracted at the pixel location. Black indicates that, on average, 0 ATPs have been extracted at the pixel location. Click on the image to the see the average direction and magnitude of the re-projection error for each pixel. Note that the vectors are scaled for better visualization. The scale bar indicates the magnitude of 1 pixel error.

2D Keypoints Table

	Number of 2D Keypoints per Image	Number of Matched 2D Keypoints per Image
Median	54804	23360
Min	41710	6249
Max	62988	36064
Mean	54413	23029

3D Points from 2D Keypoint Matches

	Number of 3D Points Observed
In 2 Images	1422015
In 3 Images	341317
In 4 Images	134694
In 5 Images	62554
In 6 Images	35105
In 7 Images	20948
In 8 Images	13064
In 9 Images	8582
In 10 Images	5604
In 11 Images	3808
In 12 Images	2489
In 13 Images	1665
In 14 Images	1052
In 15 Images	695
In 16 Images	466
In 17 Images	283
In 18 Images	172
In 19 Images	104
In 20 Images	71
In 21 Images	65
In 22 Images	47
In 23 Images	32
In 24 Images	19
In 25 Images	21
In 26 Images	15
In 27 Images	13
In 28 Images	8
In 29 Images	11
In 30 Images	3
In 31 Images	5
In 32 Images	4
In 33 Images	3
In 35 Images	2
In 37 Images	1

2D Keypoint Matches

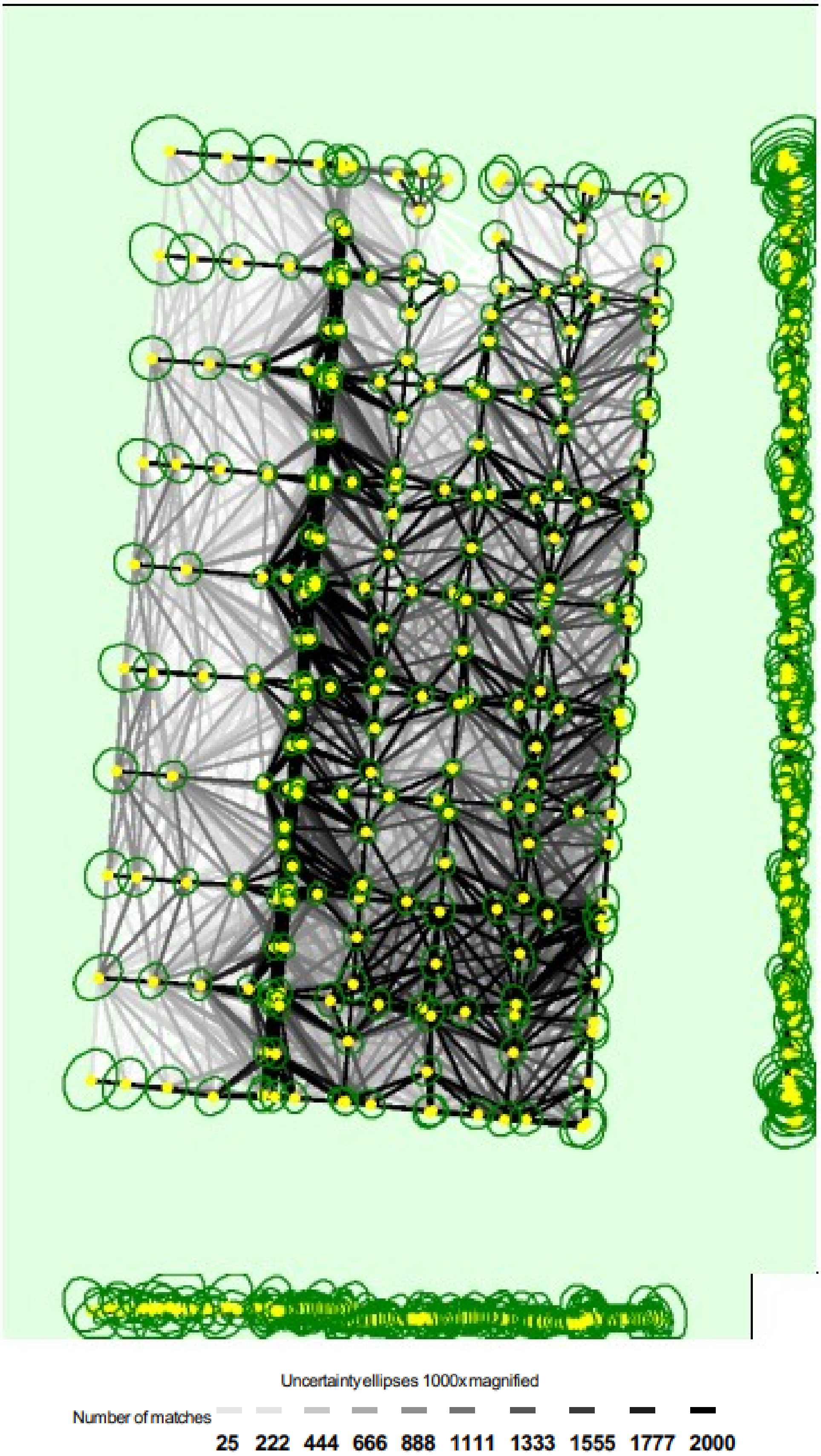


Figure 5: Computed image positions with links between matched images. The darkness of the links indicates the number of matched 2D keypoints between the images. Bright links indicate weak links and require manual tie points or more images. Dark green ellipses indicate the relative camera position uncertainty of the bundle block adjustment result.

Relative camera position and orientation uncertainties

	X[m]	Y[m]	Z[m]	Omega [degree]	Phi [degree]	Kappa [degree]
Mean	0.004	0.004	0.004	0.007	0.006	0.004
Sigma	0.001	0.001	0.002	0.002	0.002	0.001

Geolocation Details

Absolute Geolocation Variance

Min Error [m]	Max Error [m]	Geolocation Error X [%]	Geolocation Error Y [%]	Geolocation Error Z [%]
-	-15.00	0.00	0.00	0.00
-15.00	-12.00	0.00	0.00	0.00
-12.00	-9.00	0.00	0.00	0.00
-9.00	-6.00	0.84	2.53	0.00
-6.00	-3.00	5.91	7.17	0.00
-3.00	0.00	39.24	42.62	46.84
0.00	3.00	48.52	38.40	53.16
3.00	6.00	5.06	8.86	0.00
6.00	9.00	0.42	0.42	0.00
9.00	12.00	0.00	0.00	0.00
12.00	15.00	0.00	0.00	0.00
15.00	-	0.00	0.00	0.00
Mean [m]		-0.000000	0.000002	-0.000012
Sigma [m]		1.801290	2.211837	0.673320
RMS Error [m]		1.801290	2.211837	0.673320

Min Error and Max Error represent geolocation error intervals between -1.5 and 1.5 times the maximum accuracy of all the images. Columns X, Y, Z show the percentage of images with geolocation errors within the predefined error intervals. The geolocation error is the difference between the initial and computed image positions. Note that the image geolocation errors do not correspond to the accuracy of the observed 3D points.

Relative Geolocation Variance

Relative Geolocation Error	Images X [%]	Images Y [%]	Images Z [%]
[-1.00, 1.00]	95.78	94.94	100.00
[-2.00, 2.00]	100.00	100.00	100.00
[-3.00, 3.00]	100.00	100.00	100.00
Mean of Geolocation Accuracy [m]	5.000000	5.000000	10.000000
Sigma of Geolocation Accuracy [m]	0.000000	0.000000	0.000000

Images X, Y, Z represent the percentage of images with a relative geolocation error in X, Y, Z.

Geolocation Orientational Variance	RMS [degree]
Omega	2.492
Phi	2.822
Kappa	8.695

Geolocation RMS error of the orientation angles given by the difference between the initial and computed image orientation angles.

Initial Processing Details

System Information

Hardware	CPU: Intel(R) Core(TM) i7-2600 CPU @ 3.40GHz RAM: 8GB GPU: AMD Radeon HD 5450 (Driver: 15.201.1151.1008)
Operating System	Windows 10 Education, 64-bit

Coordinate Systems

Image Coordinate System	WGS 84 (EGM96 Geoid)
Output Coordinate System	WGS 84 / UTM zone 32N (EGM96 Geoid)

Processing Options

Detected Template	3D Models
Keypoints Image Scale	Full, Image Scale: 1
Advanced: Matching Image Pairs	Free Flight or Terrestrial
Advanced: Matching Strategy	Use Geometrically Verified Matching: no
Advanced: Keypoint Extraction	Targeted Number of Keypoints: Automatic
Advanced: Calibration	Calibration Method: Standard Internal Parameters Optimization: All External Parameters Optimization: All Rematch: Auto, yes

Point Cloud Densification details

Processing Options

Image Scale	multiscale, 1/2 (Half image size, Default)
Point Density	Optimal
Minimum Number of Matches	3
3D Textured Mesh Generation	yes
3D Textured Mesh Settings:	Resolution: Medium Resolution (default) Color Balancing: no
LOD	Generated: no
Advanced: 3D Textured Mesh Settings	Sample Density Divider: 1
Advanced: Image Groups	group1
Advanced: Use Processing Area	yes
Advanced: Use Annotations	yes
Time for Point Cloud Densification	01h:16m:06s
Time for Point Cloud Classification	NA
Time for 3D Textured Mesh Generation	12m:49s

Results

Number of Processed Clusters	2
Number of Generated Tiles	1
Number of 3D Densified Points	20655049
Average Density (per m^3)	449.86

DSM, Orthomosaic and Index Details

Processing Options

DSM and Orthomosaic Resolution	1 x GSD (1.74 [cm/pixel])
DSM Filters	Noise Filtering: yes Surface Smoothing: yes, Type: Sharp

Raster DSM	Generated: yes Method: Inverse Distance Weighting Merge Tiles: yes
Orthomosaic	Generated: yes Merge Tiles: yes GeoTIFF Without Transparency: no Google Maps Tiles and KML: no
Time for DSM Generation	33m:22s
Time for Orthomosaic Generation	01h:11m:41s
Time for DTM Generation	00s
Time for Contour Lines Generation	00s
Time for Reflectance Map Generation	00s
Time for Index Map Generation	00s

Appendix H – Quality report from winter survey at Nesjen

Quality Report

Generated with Pix4Dmapper version 4.3.33

Important: Click on the different icons for:

Help to analyze the results in the Quality Report

Additional information about the sections

Click here for additional tips to analyze the Quality Report

Summary

Project	Nesjenvar
Processed	2019-03-22 18:35:48
Camera Model Name(s)	FC330_3.6_4000x3000 (RGB)
Average Ground Sampling Distance (GSD)	1.38 cm / 0.54 in
Time for Initial Processing (without report)	01h:56m:57s

Quality Check

Images	median of 48636 keypoints per image	
Dataset	225 out of 226 images calibrated (99%), all images enabled, 3 blocks	
Camera Optimization	4.78% relative difference between initial and optimized internal camera parameters	
Matching	median of 21220.5 matches per calibrated image	
Georeferencing	yes, no 3D GCP	

Calibration Details

Number of Calibrated Images	225 out of 226
Number of Geolocated Images	226 out of 226

Initial Image Positions

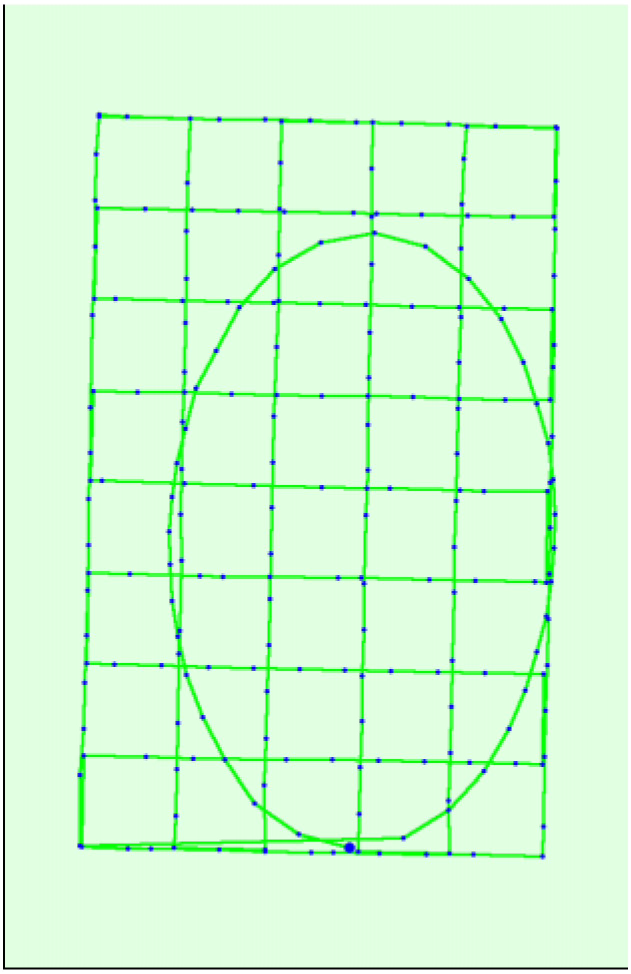


Figure 2: Top view of the initial image position. The green line follows the position of the images in time starting from the large blue dot.

Computed Image/GCPs/Manual Tie Points Positions

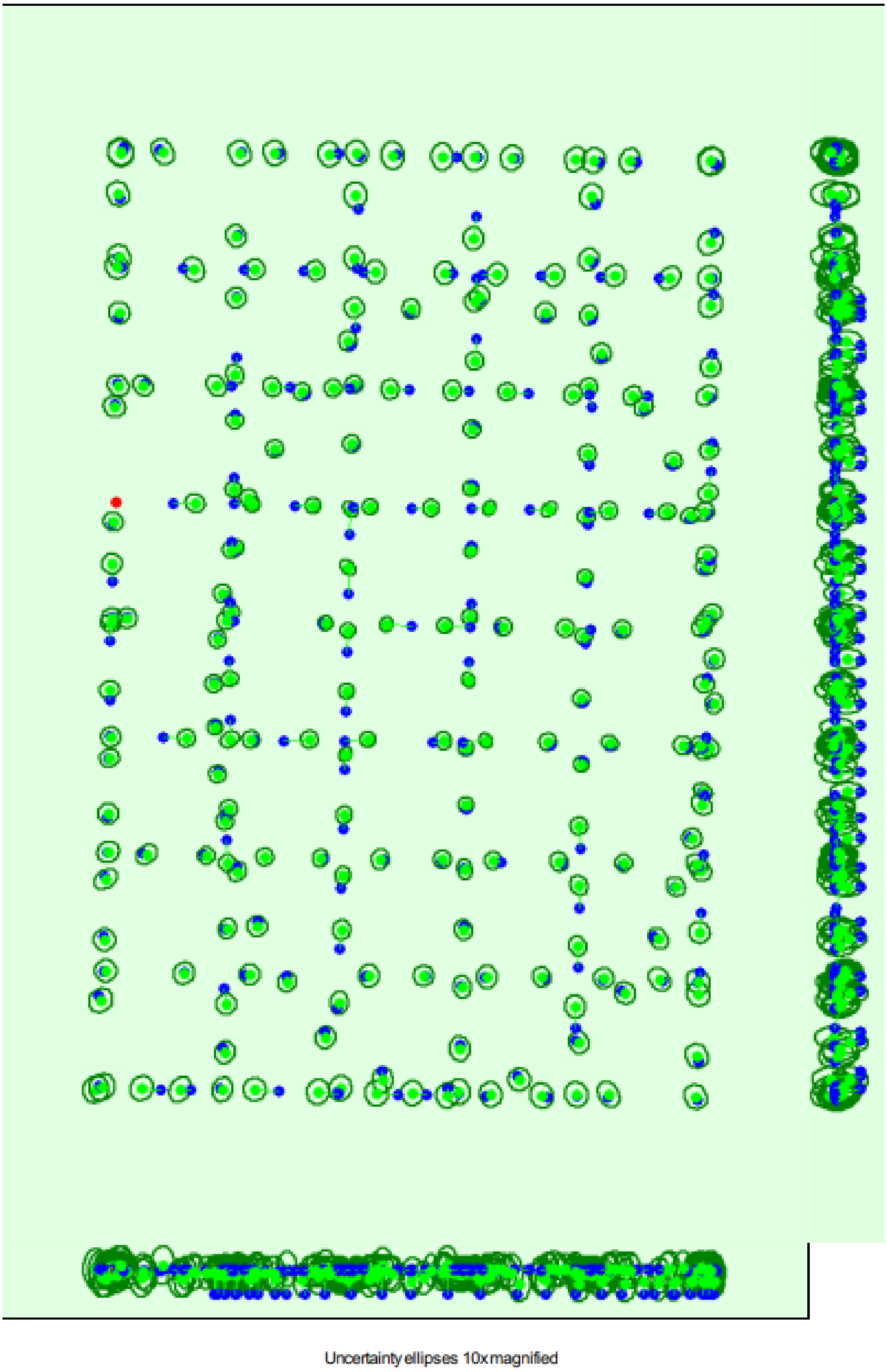


Figure 3: Offset between initial (blue dots) and computed (green dots) image positions as well as the offset between the GCPs initial positions (blue crosses) and their computed positions (green crosses) in the top-view (XY plane), front-view (XZ plane), and side-view (YZ plane). Red dots indicate disabled or uncalibrated images. Dark green ellipses indicate the absolute position uncertainty of the bundle block adjustment result.

Absolute camera position and orientation uncertainties

	X[m]	Y[m]	Z[m]	Omega [degree]	Phi [degree]	Kappa [degree]
Mean	0.203	0.210	0.338	0.110	0.116	0.116
Sigma	0.027	0.035	0.017	0.012	0.008	0.018

Bundle Block Adjustment Details

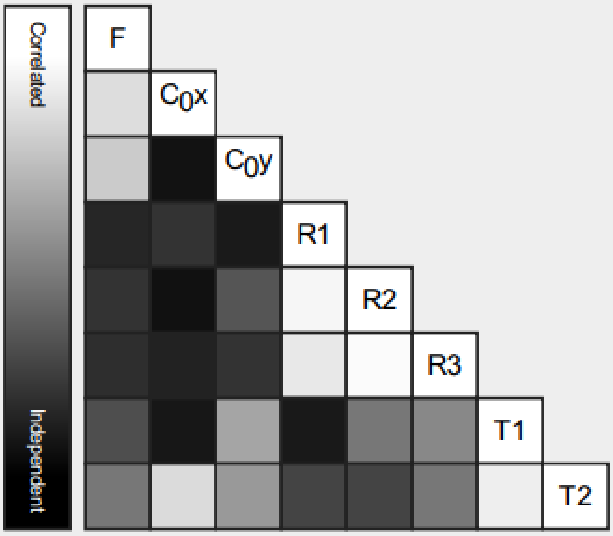
Number of 2D Keypoint Observations for Bundle Block Adjustment	4765765
Number of 3D Points for Bundle Block Adjustment	1766977
Mean Reprojection Error [pixels]	0.276

Internal Camera Parameters

FC330_3.6_4000x3000 (RGB). Sensor Dimensions: 6.317 [mm] x 4.738 [mm]

EXIF ID: FC330_3.6_4000x3000

	Focal Length	Principal Point x	Principal Point y	R1	R2	R3	T1	T2
Initial Values	2285.722 [pixel] 3.610 [mm]	2000.006 [pixel] 3.159 [mm]	1500.003 [pixel] 2.369 [mm]	-0.001	-0.002	0.000	-0.001	-0.001
Optimized Values	2395.155 [pixel] 3.783 [mm]	2070.560 [pixel] 3.270 [mm]	1495.257 [pixel] 2.362 [mm]	-0.002	-0.006	0.004	0.000	0.001
Uncertainties (Sigma)	0.156 [pixel] 0.000 [mm]	0.074 [pixel] 0.000 [mm]	0.119 [pixel] 0.000 [mm]	0.000	0.000	0.000	0.000	0.000



The correlation between camera internal parameters determined by the bundle adjustment. White indicates a full correlation between the parameters, ie. any change in one can be fully compensated by the other. Black indicates that the parameter is completely independent, and is not affected by other parameters.

The number of Automatic Tie Points (ATPs) per pixel, averaged over all images of the camera model, is color coded between black and white. White indicates that, on average, more than 16 ATPs have been extracted at the pixel location. Black indicates that, on average, 0 ATPs have been extracted at the pixel location. Click on the image to the see the average direction and magnitude of the re-projection error for each pixel. Note that the vectors are scaled for better visualization. The scale bar indicates the magnitude of 1 pixel error.

2D Keypoints Table

	Number of 2D Keypoints per Image	Number of Matched 2D Keypoints per Image
Median	48636	21220
Min	27618	424
Max	69781	38821
Mean	48995	21181

3D Points from 2D Keypoint Matches

	Number of 3D Points Observed
In 2 Images	1188506
In 3 Images	316989
In 4 Images	124515
In 5 Images	55982
In 6 Images	29678
In 7 Images	17153
In 8 Images	10585
In 9 Images	7016
In 10 Images	4590
In 11 Images	3113
In 12 Images	2199
In 13 Images	1596
In 14 Images	1188
In 15 Images	942
In 16 Images	630
In 17 Images	564
In 18 Images	403
In 19 Images	321
In 20 Images	248
In 21 Images	194
In 22 Images	165
In 23 Images	96
In 24 Images	90
In 25 Images	69
In 26 Images	48
In 27 Images	31
In 28 Images	24
In 29 Images	22
In 30 Images	6
In 31 Images	5
In 32 Images	3
In 33 Images	3
In 34 Images	1
In 35 Images	1
In 40 Images	1

2D Keypoint Matches

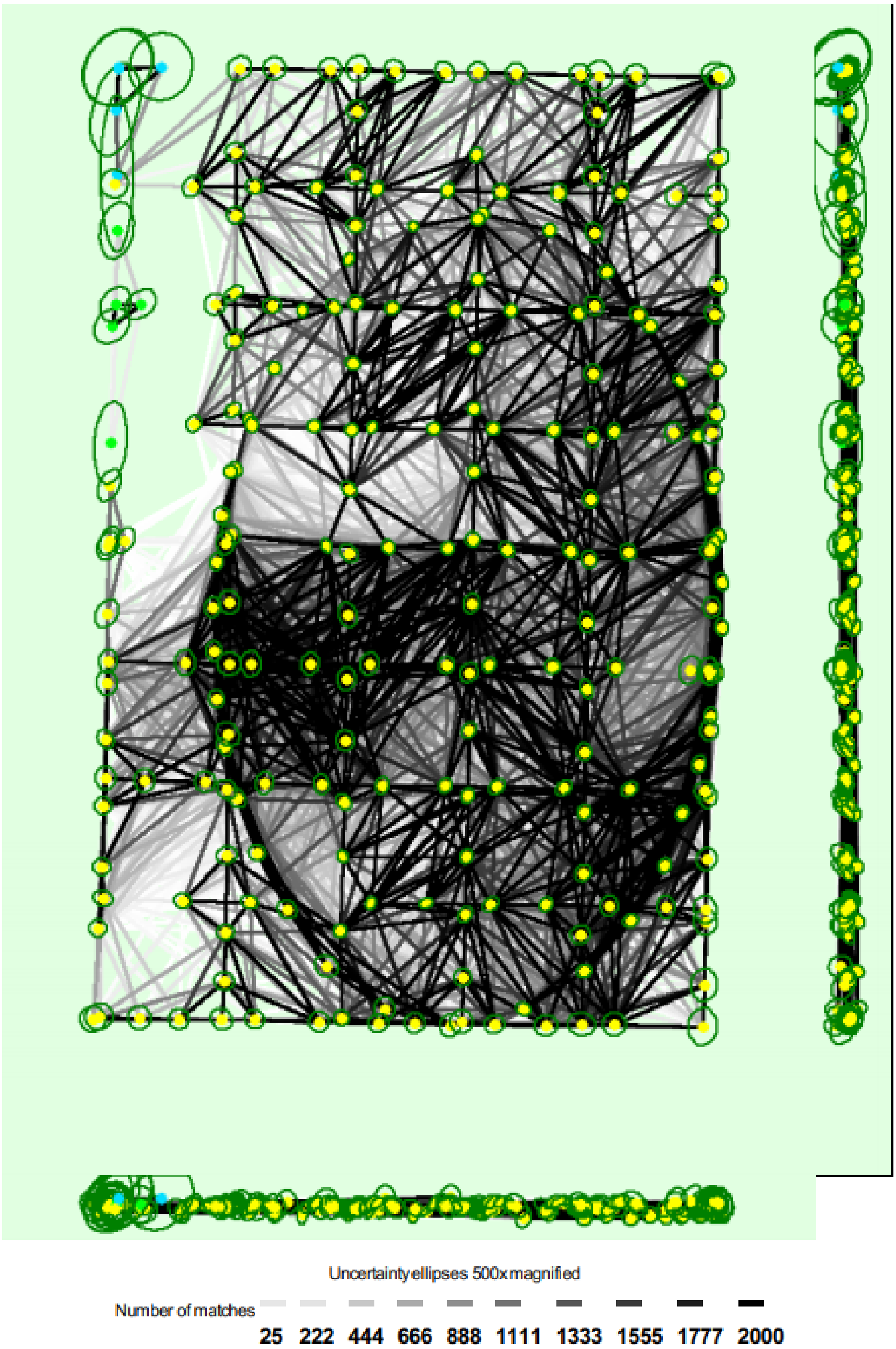


Figure 5: Computed image positions with links between matched images. The darkness of the links indicates the number of matched 2D keypoints between the images. Bright links indicate weak links and require manual tie points or more images. Dark green ellipses indicate the relative camera position uncertainty of the bundle block adjustment result.

Relative camera position and orientation uncertainties

	X [m]	Y [m]	Z [m]	Omega [degree]	Phi [degree]	Kappa [degree]
Mean	0.004	0.004	0.004	0.008	0.007	0.006
Sigma	0.002	0.003	0.002	0.004	0.003	0.005

Geolocation Details

Absolute Geolocation Variance

Min Error [m]	Max Error [m]	Geolocation Error X [%]	Geolocation Error Y [%]	Geolocation Error Z [%]
-	-15.00	0.00	0.00	0.00
-15.00	-12.00	0.00	0.00	0.00
-12.00	-9.00	0.00	0.00	0.00
-9.00	-6.00	0.00	0.00	0.44
-6.00	-3.00	6.67	6.22	5.78
-3.00	0.00	43.56	50.22	21.33
0.00	3.00	43.11	37.78	72.44
3.00	6.00	6.67	5.78	0.00
6.00	9.00	0.00	0.00	0.00
9.00	12.00	0.00	0.00	0.00
12.00	15.00	0.00	0.00	0.00
15.00	-	0.00	0.00	0.00
Mean [m]		0.007735	0.005245	-0.016183
Sigma [m]		1.622203	1.628341	1.570363
RMS Error [m]		1.622221	1.628349	1.570447

Min Error and Max Error represent geolocation error intervals between -1.5 and 1.5 times the maximum accuracy of all the images. Columns X, Y, Z show the percentage of images with geolocation errors within the predefined error intervals. The geolocation error is the difference between the initial and computed image positions. Note that the image geolocation errors do not correspond to the accuracy of the observed 3D points.

Relative Geolocation Variance

Relative Geolocation Error	Images X [%]	Images Y [%]	Images Z [%]
[-1.00, 1.00]	98.22	99.56	100.00
[-2.00, 2.00]	100.00	100.00	100.00
[-3.00, 3.00]	100.00	100.00	100.00
Mean of Geolocation Accuracy [m]	5.000000	5.000000	10.000000
Sigma of Geolocation Accuracy [m]	0.000000	0.000000	0.000000

Images X, Y, Z represent the percentage of images with a relative geolocation error in X, Y, Z.

Geolocation Orientational Variance	RMS [degree]
Omega	2.149
Phi	4.330
Kappa	7.122

Geolocation RMS error of the orientation angles given by the difference between the initial and computed image orientation angles.

Initial Processing Details

System Information

Hardware	CPU: Intel(R) Core(TM) i7-2600 CPU @ 3.40GHz RAM: 8GB GPU: AMD Radeon HD 5450 (Driver: 15.201.1151.1008)
Operating System	Windows 10 Education, 64-bit

Coordinate Systems

Image Coordinate System	WGS 84 (EGM96 Geoid)
Output Coordinate System	WGS 84 / UTM zone 32N (EGM96 Geoid)

Processing Options

Detected Template	3D Models
Keypoints Image Scale	Full, Image Scale: 1
Advanced: Matching Image Pairs	Free Flight or Terrestrial
Advanced: Matching Strategy	Use Geometrically Verified Matching: no
Advanced: Keypoint Extraction	Targeted Number of Keypoints: Automatic
Advanced: Calibration	Calibration Method: Standard Internal Parameters Optimization: All External Parameters Optimization: All Rematch: Auto, yes

Point Cloud Densification details

Processing Options

Image Scale	multiscale, 1/2 (Half image size, Default)
Point Density	Optimal
Minimum Number of Matches	3
3D Textured Mesh Generation	yes
3D Textured Mesh Settings:	Resolution: Medium Resolution (default) Color Balancing: no
LOD	Generated: no
Advanced: 3D Textured Mesh Settings	Sample Density Divider: 1
Advanced: Image Groups	group1
Advanced: Use Processing Area	yes
Advanced: Use Annotations	yes
Time for Point Cloud Densification	01h:02m:21s
Time for Point Cloud Classification	NA
Time for 3D Textured Mesh Generation	09m:35s

Results

Number of Processed Clusters	4
Number of Generated Tiles	1
Number of 3D Densified Points	16632197
Average Density (per m^3)	813.13

DSM, Orthomosaic and Index Details

Processing Options

DSM and Orthomosaic Resolution	1 x GSD (1.38 [cm/pixel])
DSM Filters	Noise Filtering: yes Surface Smoothing: yes, Type: Sharp

Raster DSM	Generated: yes Method: Inverse Distance Weighting Merge Tiles: yes
Orthomosaic	Generated: yes Merge Tiles: yes GeoTIFF Without Transparency: no Google Maps Tiles and KML: no
Time for DSM Generation	21m:31s
Time for Orthomosaic Generation	01h:04m:55s
Time for DTM Generation	00s
Time for Contour Lines Generation	00s
Time for Reflectance Map Generation	00s
Time for Index Map Generation	00s

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