GISY6044 – Applied Geomatics Term Project

Part 1: ***Small Scale UAV Data Acquisition with SfM-MVS Photogrammetry Principals: A Best Practice Manual and Review towards Accurate Topographic Mapping***

Submitted to Nathan Crowell
Applied Geomatics Research Group

By Rafael Del Bello
Centre of Geographic Sciences
May 2020

Table of Contents

Abbreviations

AGL: Above Ground Level

AGRG : Applied Geomatics Research Group

CARs : Canadian Aviation Regulations

CP: Control Point

DG: Direct Georeferencing

DGPS: Differential Global Positioning System

GCPs : Ground Control Points

GNSS : Global Navigation Satellite System

GSD : Ground Sampling Distance

GPS : Global Positioning System

MVS : Multi-View Stereo

RPAS : Remotely Piloted Aircraft System

SfM : Surface from Motion

SfM-MVS : Surface from Motion and Multi-View Stereo combined

SFOC : Special Flight Authorization Request

SOP: Standard Operating Procedure

UAS: Unmanned Aerial System

UAV: Unmanned Aerial Vehicle

TC : Transport Canada

Contact Information

Nathan Crowell, M Sc.
Client - Research specialist and project coordinator
Applied Geomatics Research Group (AGRG)
Middleton, Nova-Scotia
Nathan.Crowell@nscc.ca
902-824-3953

Rafael Del Bello, B Sc.
Student - Advanced diploma in GIS and remote sensing
Centre of Geographic Sciences (COGS)
Lawrencetown, Nova-Scotia
Delbello.Rafael@gmail.com
514-917-5232

Acknowledgement

The following work was created towards the completion of GISY6044 - Applied Geomatics Research Project as a requirement for the Advanced Diploma in Geographic Sciences and Remote Sensing at the Centre of Geographic Sciences, Nova Scotia. It was created for and with the support of the Applied Geomatics Research Group (AGRG), who provided support, data, and access to hardware required for processing.

The author would also like to thank Rob Hodder from the faculty at the Centre of Geographic Sciences, and Nathan Crowell from Applied Research, who both showed exceptional leadership and support albeit difficult conditions provoked by the COVID-19 health crisis.

1. Project Overview

In the last decade, the use of remotely piloted aircraft systems (RPAS), also known as unmanned aerial vehicles(UAVs), unmanned aerial systems (UAS), or drones, has seen a large increase in geomatics and geomorphic research applications(Dering et al, 2019; Giordan et al., 2018). In part due to their relatively low cost and accessibility, but also because of key advancement in the field computer vision algorithms, drones have become an alternative for topographic mapping and 3D modeling comparable to traditional surveying methods (Smith, 2015). However, with the wide array of platforms made available and a steady stream of information stemming from sources of varying credibility, deciding on the appropriate approach to perform aerial surveys can be a daunting task. This project involves three deliverable that aim to fill this gap:

i) the following document entitled “Small Scale UAV Data Acquisition using SfM-MVS Photogrammetry Principals” will present guiding principals behind digital UAV-based planning and collection for geoscience ;

ii) within the project package, a file named “delbello_Agisoft-Intro-Turorial.pdf” presents the end-to-end workflow in processing UAV imagery using Agisoft Metashape Professional;

iii) within the project package, a file named “delbello_Gradual-Selection-Report.pdf” presents a preliminary report for a sparse point cloud filtering technique applied using a script based on the Agisoft Python API.

2. Introduction

The main purpose of this document is to provide the user with the information required to produce precise and repeatable mapping products stemming from surface from motion (SfM-MVS) photogrammetry principals. It will touch on both the planning and operational facets of a UAV collection within Canada, and also provide information gathered from the literature to help perform safe and professional surveys, guide future research, and inform the reader about the potential errors that can stem from this type of collection.

After reading this document, the user should have a better understanding of the following topics:

- current high-level regulations governing the use of UAV in Canada and where to obtain more information;
- notions on SfM-MVS photogrammetry algorithm workflows and how they differ from classical photogrammetry methods;
- considerations during the mission planning stage including survey design, flight parameters, and hardware requirements;

- considerations during the image acquisition stage including optimal environmental conditions, camera settings, and ground control distribution.

To provide a general road map to the topics discussed in this paper, Figure 1 shows an overview of the steps required for a typical small-scale UAV-based survey. These topics will be proceeded by a small introduction to the general regulation governing UAV operations in Canada, as well as a basic overview of the photogrammetry workflow.

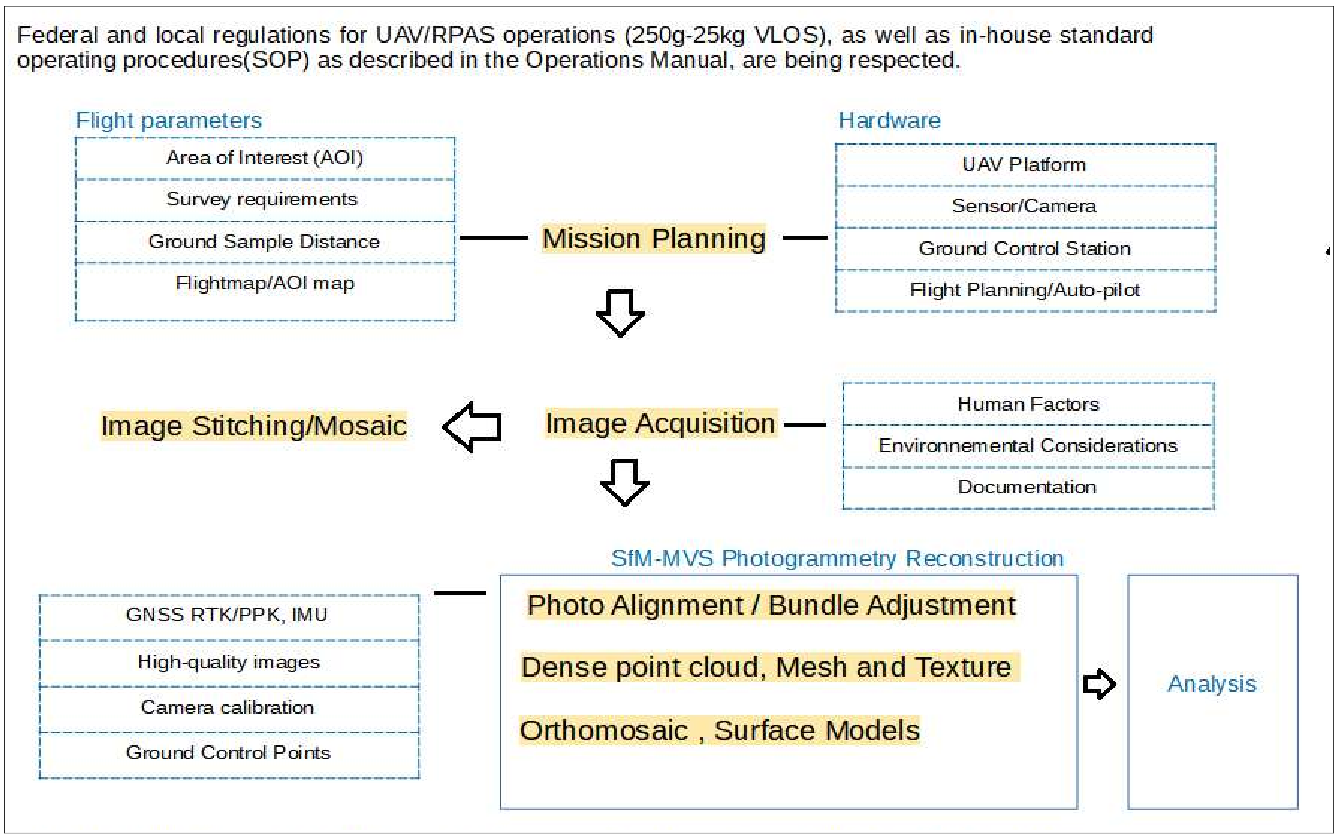


Figure 1: Steps involved in photogrammetry workflow. Adapted from Nex and Remondino(2014). UAV for 3D mapping applications : a review. 1–15. https://doi.org/10.1007/s12518-013-0120-x

Note: flight requirements and goals, as well as the topographic surfaces, vary greatly vary from project to project. An attempt was made to present information that can be applied in various situations, however, the information presented in the following document may not be appropriate for all situations. This should be considered as a general guide. It is recommended to communicate with your project manager or assigned supervisor before proceeding with the implementation of an aerial survey.

3. Regulatory Framework

In Canada, the use of UAVs is regulated and managed by Transport Canada (TC). UAV systems that weight over 250g must be registered, labelled, and operated by compliant operators who hold a drone pilot certificate classified as basic or advanced. On the other hand, systems over 25kg require a special flight authorization certificate (SFOC). Given certain criteria that must be met, the advanced license enables operators to fly within controlled airspace (Class C) or during organized events. Otherwise, the UAV must remain within class G airspace, from a distance of 5 nautical miles from registered airports, and never in protected parks or active emergency zones such floods, active fires, or search and rescue missions. More importantly, flights must always be operated safely while minimizing the risk of endangering other people, private property, wildlife, or users of the airspace. Finally, current legislation only allows for flights in visual line of sight (VLOS), at altitudes no greater than 120 m (400ft), and for Canadians or permanent residents.

More information about the different types of licenses, the procedure to obtain them, and official information about regulations can be obtained through the official Transport Canada website :

General information:
https://www.tc.gc.ca/en/services/aviation/drone-safety/flying-drone-safely-legally.html

Drone Management Portal(permit and registration):
https://clegc-gckey.gc.ca

Furthermore, be aware that as civilians who operate within the Canadian airspace, operators can be held liable for actions going against the Canadian Aviation Regulations (CARs), the Criminal Code, and laws regarding privacy:

Canadian Aviation Regulation:
https://laws-lois.justice.gc.ca/eng/regulations/sor-96-433/page-1.html

Canadian Crimal Code:
https://laws-lois.justice.gc.ca/eng/acts/c-46/

Privacy Laws:
https://www.tc.gc.ca/en/services/aviation/drone-safety/privacy-guidelines-drone-users.html

3.1 Operations Manual

All crew members involved in the operation or manipulation of UAV related material during a mission is required to have read, understood, and agreed to follow AGRG's operational procedure as established in the Operation Manual. This document should be made available to all requesting crew members and should be present on-site for each mission.

4 Surface from Motion (SfM) Photogrammetry

Traditional photogrammetry is the science of obtaining precise 3D measurements from pairs of 2D photographs and has a long-established history (Aber et al., 2019). It effectively reverses the process of photography by reconstructing an object space using the image space, and works on the premise that given two or more showing the same object in two different positions, also known as stereo photographs, a precise 3D coordinate of points found in both photos can be obtained (Linder, 2006).

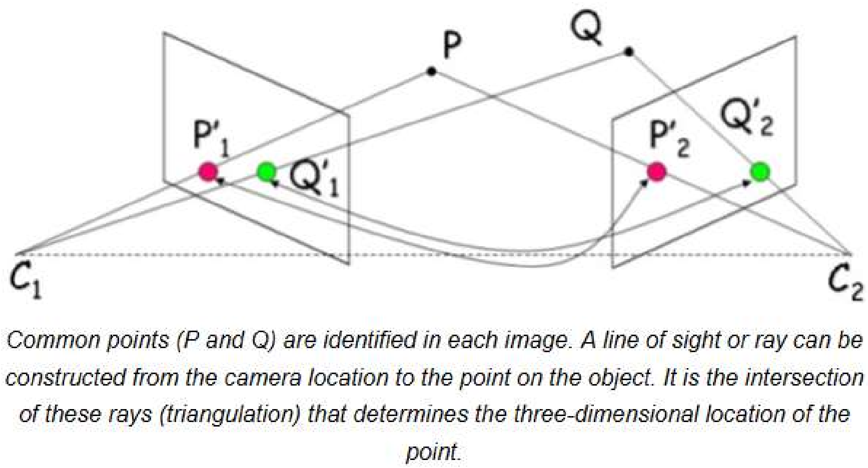


Figure 2: Basic principal of point measurements using traditional photogrammetry
Humbolt State University.GSP216 - Introduction to Remote Sensing. Structure From Motion(SfM). Accessed May 1, 2020 from: http://gsp.humboldt.edu/OLM_2017/courses/GSP_216_Online/lesson8-2/SfM.html

With a trend diverging from the traditional analog and optical-mechanical methods, current workflows have become more concerned with image analytical properties in digital formats (Aber et al., 2010). These new methods of 3D reconstruction are based on the same mathematical principals, but have adopted the use of computer-aided vision and image algorithms. In turn, this has brought about the need to differentiate the new workflow which combines Surface from Motion (SfM) and Multi-View Stereo (MVS). SfM-MVS differs from traditional methods for two distinct reasons. First, it requires multiple overlapping photographs instead of a single pair for feature extraction and reconstruction, and secondly, it can solve for scene geometry, camera positions, and camera orientations without the need for known ground coordinates (Westoby et al. 2012).

In their book about small-format aerial photography, James Aber and Irene Marzolf(2019) provide a detailed description of the SfM-MVS workflow which can be summarized as follow:

> First, key-points must be extracted from matching features in the photographs using an object recognition system, usually the Scale Invariant Feature Transform (SIFT). With enough matching points, the initial bundle-adjustment (BA) is applied for the 3D reconstruction of interior and exterior camera orientation, as well as for camera self-calibration. The BA is a least-squares optimization enabling the estimation of 3D positions and camera poses, ultimately allowing for the creation of the sparse point cloud (Meinen & Robinson, 2020). The model output is then scaled or georeferenced using control data (GCPs), or through direct georeferencing (DG). This is followed by the creation of additional points using the method multi-view stereo (MVS) algorithm, effectively creating the photogrammetric dense point cloud used for analysis (p.30).

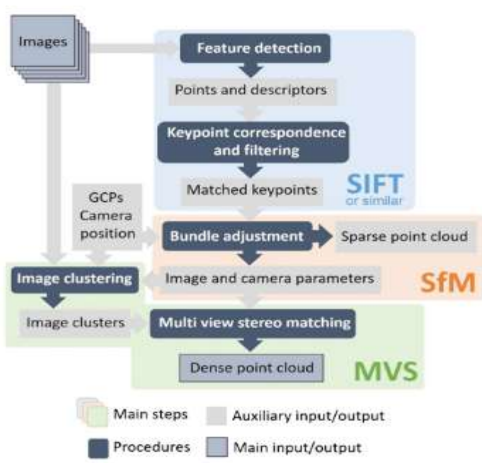


Figure 3: Modern SfM-MVS algorithm processing chain

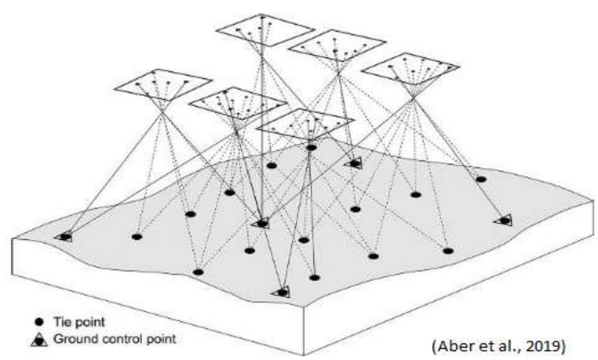


Figure 4: Bundle-Adjustment of camera poses using control data and tie points from initial sparse cloud

5. Mission Planning

Planning a UAV photogrammetric collection involves the careful consideration of various flight parameters, hardware, and sensor settings. These elements must be chosen and work towards a set of constraints usually defined by a project or clients need(s). Those choices leading up to the actual fieldwork are important as they can be time-consuming and involve costly material, often determinant to the effectiveness and success of a mission.

To be able to appropriately plan for a photogrammetric collection, a project should be properly defined and contain at least the following:

- the required pixel resolution or ground sampling distance (GSD);
- a well-established description of the site or object of interest (AOI) to be surveyed;
- the goal, the required accuracy of the survey in X, Y and Z, and the deliverable formats.

5. 1 Ground Sample Distance

When discussing UAV-based mapping, ground sample distance (GSD) refers to the spatial resolution of the image product. The required spatial resolution is important seeing as it will determine additional parameters also crucial to the mission, including the smallest resolvable object in the image (the details), flight height (which can affect the choice of the platform/sensor), final point cloud density, and the accuracy of the survey (i.e an image with a resolution of 10cm cannot be accurate to 1mm).

GSD is a function of flight height, sensor focal length, and sensor pixel pitch. It can be calculated with the following formula:

$$GSD = \frac{2H \times \arctan(S_{\mathrm{det}})}{2f} \approx \frac{H \times S_{\mathrm{det}}}{f}$$

where H is flight height , S_{det} the pixel pitch (width per pixel on sensor), and f the sensor's focal length(Connor et al., 2017).

With the known flight height required for a survey, the traditional flight planning workflow would require the calculations of the image footprint and image overlap to determine flight speed and image capture intervals (Aber, 2019) . Examples of such calculations have been explored numerous times and remain the preferred method when planning survey areas involving complex topographic variation. When dealing with less intricate AOI, the use of dedicated third-party UAV route planning software can facilitate survey design by automating the calculation based on predetermined sensor metrics, desired GSD, and image overlap. These softwares can generate the optimal flight lines to cover the AOI while simultaneously minimizing flying time, images count, and energy consumption (i.e battery use).

Finally, because the AOI is likely to involve varying ground-level elevation due to the natural topography of the scene, it is important to set the flight height (or distance to object for vertical surfaces) as the farthest point away from the camera (Federman et al., 2017). This approach ensures that the lowest point of the survey will meet the required resolution for the project. Lastly, given the fact that most small UAV platform record relative heights(AGL), consulting published elevation data of the survey area during the planning process can help identify the areas with the greatest depression and ensure GSD coverage across the AOI.

5.2 Survey Area

Following the determination of nominal flight altitude, the extent of the AOI needs to be properly defined and integrated into the flight path planning software. As for most remote-sensing collection, it is recommended to include a small buffer as a way to eliminate the risk of having a gap in the imagery. Furthermore, when possible a survey block with an East-West orientation is recommended to minimize the effect of shadows. However, if the AOI is elongated in shape, the flight lines should be oriented along the longer dimension to minimize energy consumption.

Additionally, these are other consideration to account for :

- an AOI devoid of distinct features (eg. forests, agricultural plots) may be unsuitable for SfM-MVS as they result in a lack of key-point matching during the SIFT algorithm procedure. This has the effect of greatly degrading point cloud densities and derived products (Iglhaut et al., 2019; Westoby et al., 2012) ;
- an AOI that contains shiny or reflective surfaces may also cause problems for SfM-MVS because feature appearance will vary between camera poses (Smith et al., 2015). Choosing a day with cloud overcast could help in that situation as it would produce more diffuse lighting conditions.
- the position of the site survey in relation to the landscape is important to consider as it may influence wind patterns which can affect UAV stability (Aber et al., 2019b).

Finally, for measures related to safety, crew members on-site should be aware of the following: the location of entry and exit points for site evacuation in case of an emergency, the location of physical obstacles that could interfere with the UAV platform during flight maneuvers such as trees, wires, or power lines, and finally, the presence of kindergartens, schools, or other public spaces that could increase the likelihood of passerby interfering with the operation.

5.3 Image Overlap

To ensure high image redundancy and numerous matching key-points, SfM-MVS photogrammetry requires high imagery overlap with recommended value usually around 80%-60% for front and side overlap respectively (or along-track and across-track) (Mosbrucker, et al., 2017; Nex & Remondino, 2014). It should be noted that current research and literature provides no fit-for-all solution to achieve effective overlaps and a variety of combination has been used successfully, sometimes going as high as

90%-70% for landscape areas presenting more complex topography (Borrelli, et al. 2019). Finally, this parameter can be programmed using the flight planning software or obtained through traditional aerial survey planning.

5.4. Camera Orientation

There are two categories of camera orientation for photogrammetry, namely nadir and oblique. Nadir represents a camera orientation looking down and directly perpendicular to the ground level, while oblique refers to the case where the camera is tilted slightly upwards. The use of oblique imagery, sometimes referred to as “off-nadir” or “tilted”, is useful to obtain additional information of hidden features or complex geometry that cannot be achieved with traditional nadir configurations. For this reason, its use has been established as the preferred method for buildings or cultural heritage sites photogrammetry (Chiabrando et al., 2016). Because current UAVs on the market now provide gimbaled sensors, oblique imagery has become more accessible and is increasingly being used to complement nadir imagery.

A recent article by scientists at the University of Calgary which explored over 150 acquisition scenarios has been able to quantify some of the benefits of this technique specifically for a scene with complex topography. The research provides a general summary of their findings which explored the use of nadir, oblique, nadir-oblique combinations, as well as overlap considerations and bring the following recommendations :

- image sets that combine both nadir and oblique are preferred over image sets using only one angle;
- a higher overlap generally corresponds to better results for sets combining both oblique and nadir sets;
- single-angle image sets with lower angles are prone to large systematic errors (Nesbit & Hugenholts, 2019).

It should be noted that the method is still being explored and literature provides examples where the technique should not be applied. For instance, a study looking at the addition of oblique images for flat agricultural plots reported an increase of both surveying time (threefold) and processing time (fivefold) while limited benefits to the accuracy was obtained (Meinen and Robinson, 2020). The failure of positive results on accuracy for that case-study may also be due to poor image texture lacking distinct features for the key point matching algorithm.

5.5 Flight Patterns

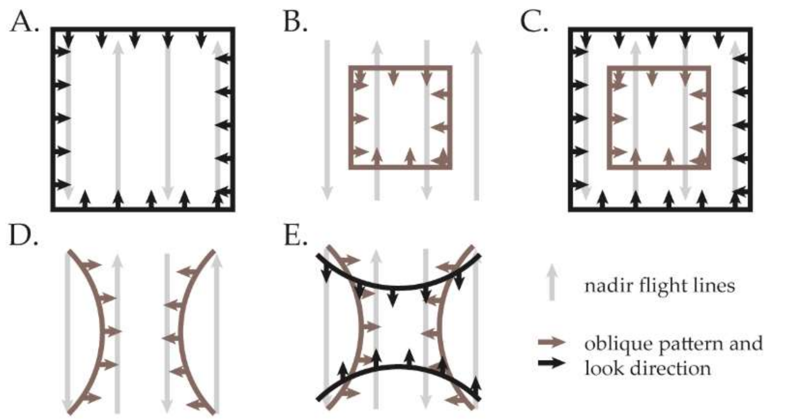
Flight patterns for topographic mapping usually take the form of single grids (back and forth) or a double grid, sometimes referred to as cross-hatch or double-gridding, which are simply two grids positioned orthogonal to each other(Ali & Abed, 2019). These patterns are made available in most flight planning software, and while software such as Pix4D only allow single grids to be created, the solution is to program two single grid missions perpendicular to each other. The benefits of applying a double grid may originate from an increase in image redundancy and from minimizing the risk of information gap caused by the presence of vertical surfaces(Nesbit & Hugenholtz, 2019). Another consideration is the fact that this technique increases the number of images to be processed, therefore it's use should be weighed accordingly.

Finally, just like the oblique and nadir camera orientation methods, current literature indicates some contradicting results in regards to the efficacy of using double grids. For instance, some reports show positive impact on accuracy for terrain mapping showing small undulation, concluding that the difference in flight direction helps determine a more accurate estimation of the principal point, which results in greater accuracy especially in the Z component (Gerke & Przybilla, 2016). Alternatively, Ali and Abed (2019) show results with a negative impact on both the XY and Z accuracy, claiming that the increase in shear image numbers also increased the sources for error (2019).

5.6 Image Block Geometry

Image block geometry refers to the combination of all previously stated elements (flight extent, flight lines, flight line orientations, camera orientation) and has a profound impact of the accurate reconstruction of topographic shape, particularly by affecting point density and increasing the risk of dome-like deformation(James & Robson, 2014).

It has been shown that the strengthening of the image block can occur by incorporating nadir imagery supplemented with oblique and convergent imagery, sometimes from multiple scales (James, & Robson, 2014; Mosbrucker et al., 2017). If incorporating convergent imagery, the angular change should be no greater than 25-30 degrees between camera poses, while 15-20 degrees has been recommended(Smith et al., 2015).



Nesbit, P. R., & Hugenholtz, C. H. (2019). Enhancing UAV-SfM 3D model accuracy in high-relief landscapes by incorporating oblique images. Remote Sensing, 11(3), 124. https://doi.org/10.3390/rs11030239

Figure 5: Examples of efficient image-block geometry

6. Camera Settings

To obtain as much information as possible in the image and to aid in the key point matching during the SfM-MVS workflow, it is important to carefully configure the camera settings by prioritizing exposure and focus (Mosbrucker et al., 2016). Proper exposure can be achieved by setting the appropriate ISO, shutter speed, and aperture, also known as the exposure triangle. In their paper discussing cameras and aerial surveys, author Conor, Smith, and James (2017) provide a clear introduction to the image capture process as it relates to photogrammetry. They suggest the following camera configuration:

- ISO should be set a low as possible to ensure proper exposure, maximize dynamic range, and reduce noise. Typical ISO values are between 100-800;
- Shutter speed must be determined by considering proper exposure and minimizing motion blur. Image motion blur is minimized by keeping the distance traveled by the UAV under 1.5 times the GSD. The typical range for shutter speed is 1/250s to 1/1000s;
- Aperture will depend on the depth of field, but for flight heights above 20m effective aperture is usually in the medium range of f/5.6 – f/11.;
- Given the previous setting configuration, the focus can be set to obtain sharp imagery of features on the ground. Typically set at infinity for UAV platforms.

6.1 Lens

When working with a UAV system that has an interchangeable lens, the recommended effective focal length should be between 28-35 mm, and using lenses wider than 35mm will increase the risk of distortion issues affecting the quality of the end products (James et al. 2012). Furthermore, the use of a zoom lens or applying varying focal lengths during the same capture is not recommended. Better results are achieved using constant camera parameters during the bundle adjustment procedure (Smith et al., 2015).

6.2 Camera Calibration

Camera calibration is the process of estimating intrinsic camera parameters and is crucial in reducing errors associated with lens distortions and, as a consequence, has the effect of reducing the propagation of systematic errors onto topographic surfaces (James et al., 2020). There exist various methods of calibrating sensors using coded targets before a collection and these can be appropriate for high-quality metric cameras. However, this method assumes constant measurement of camera parameters during photo capture which cannot be guaranteed with relatively unstable, consumer-grade digital sensors (Thoeni et al., 2016). As reported by various studies, the method of camera self-calibration applied during the photogrammetric bundle adjustment process remains the preferred method (James & Robson, 2014; Nesbit & Hugenholtz, 2019).

6.3 File Format

Some UAV platform provide the ability to save images both in RAW(DNG, 32-bit, full dynamic range) and JPEG(8-bit, compressed). RAW is known to preserve a greater dynamic range, feature less noise, and be an excellent choice for post-processing correction(Mosbrcuker et al., 2017). However, this format is generally not accepted in all software, and it’s size output (~ 40 Mb in RAW compared to ~8Mb as JPEG) can make the storing and processing problematic (James et al., 2014). It is therefore preferable to acquire and process imagery in JPEG, unless specified to do so otherwise.

6.4 Rolling Shutter

Shutters equipped on UAV sensors are either rolling shutters (CMOS) or global shutters. The former will capture the scene using a scanning method and will introduce distortion in the presence of moving features(Seker, 2020). To remove this effect, the UAV should be operated at low speed and employ a fast shutter speed. Alternatively, images can also be captured while the platform is stationary. If higher speed is required to increase total survey coverage, a rolling shutter compensation can be enabled in certain photogrammetry software such as Agisoft Metashape

7. Ground Control Points (GCPs)

Just like most tradition surveying methods, photogrammetry benefits greatly from control data and should always be implemented if the goal is to produce precise topographic surfaces(Ali & Abed, 2019; Mirko et al., 2019; Tonkin & Midgley, 2016) . The importance of ground control points (GCPs) comes from their use in georeferencing the SfM product (position), and from providing constraints within the bundle adjustment thus fitting the model points to their real position(shape) as uniformly and accurately as possible(James, 2017). Lastly, they have been shown to be highly effective in reducing the doming effect that can be caused by systematic errors formed by weak image geometry or lens distortion(James et al., 2014; Laporte-Fauret et al., 2019; Meinen & Robinson, 2020; Nesbit & Hugenholtz, 2019)

Currently, literature can agree on these three points: 3 GCPs represents the bare minimum to georeference a survey, adding 5 GCPs seems to greatly increase positional accuracy, and lastly, after a certain value an excessive amount of GCPs will stop increasing accuracy (Linder, 2006). Therefore, because every survey has its distinct geometry, attention should be made not to apply generalization. However, a group of Australian scientists looking specifically at small-scale UAV design for geomorphic analysis has been able to propose the following recommendations:

- there should be a minimum of 20 GCPs evenly distributed across the survey area;
- the locations of these control points should be measured with high precision instruments with differential GPS or total station being favored;
- from the 20 controls, half (10) of those should be used to rectify the model, and the other half (10) should be used to measure the georeferencing errors across the model(checkpoints);
- error between predicted and measured locations should be reported using the Root Mean Square method (Dering et al., 2019).

8. Survey and Operational Map

Transport Canada requires the survey site of more complex missions to be assessed by identifying safety elements such as the position and placement of entrance, obstacles, public spaces, and location to airports. To perform a robust collection that can be repeatable, it is also recommended to include in the flight map and site assessment plan the intended flight parameters. As proposed by James et al., these should include the intended platform used and key survey design elements such as GSD, flight height, overlap, survey controls, camera settings, and reasoning behind specific flight geometries (2019). This document, along with the information provided in it, can then be used when reporting on the collection's performance or deviation. Finally, it is recommended to present this plan to the project manager for review before an acquisition in order to add a safety net, increase operational success, and ensure that the project goals will be met.

9. Environmental Condition

A careful assessment of weather conditions leading up to the collection is recommended. Weather forecasts should be consulted multiple days before the survey and used to schedule an appropriate day clear of negative flight and illumination condition. Additionally, including a re-collection day may be beneficial for a crucial project that requires deadlines being met. Additional considerations include:

- sun-angle height no less than 30° above the horizon to provide sufficient illumination, reduce glint. Typically a few hours before or after mid-day are recommended;
- for complex geomorphic surveys that include textured material, light cloud-cover may provide positive diffuse illumination and reduce shading, glint, and surface reflection;
- wind conditions transverse to flight line will affect UAV stability and are not recommended;
- NOTAMs and METARs should be consulted for precise aeronautical conditions .

10. Closing Remarks

This document provided an overview of collection techniques for UAV-based topographic mapping. SfM-MVS photogrammetry is highly dependent on image analytics, quality, and redundancy. Because of this, the preferred collection method has diverged greatly from traditional methods and involves numerous considerations, especially when measurement accuracy and precise topographical models are required. The survey design is of particular importance and has the most influence on the point cloud. Finally, because this topic is still in its infancy, the techniques presented in this document does not provide a fit-for-all solution. Instead, flight parameters and image block geometry should be documented and adapted to individual site characteristics and mission goals.

References

Aber, J. S., Marzolff, I., Ries, J., & Aber, S. E. W. (2019). *Small-Format Aerial Photography and UAS Imagery: Principles, Techniques and Geoscience Applications*. Academic Press.
***A book about traditional and modern photogrammetry techniques**

Ali, H. H., & Abed, F. M. (2019). The impact of UAV flight planning parameters on topographic mapping quality control. *IOP Conference Series: Materials Science and Engineering*, *518*(2). https://doi.org/10.1088/1757-899X/518/2/022018

Borrelli, L., Conforti, M., & Mercuri, M. (2019). Lidar and UAV system data to analyse recent morphological changes of a small drainage basin. *ISPRS International Journal of Geo-Information*, *8*(12). https://doi.org/10.3390/ijgi8120536

Chiabrando, F., Donadio, E., & Rinaudo, F. (n.d.). *SfM FOR ORTHOPHOTO GENERATION: A WINNING APPROACH FOR CULTURAL HERITAGE KNOWLEDGE*.

Connor, J. O., Smith, M. J., & James, M. R. (2017). *Cameras and settings for aerial surveys in the geosciences : Optimising image data*. https://doi.org/10.1177/0309133317703092
***A paper providing an overview of camera settings with a detailed discussion on the best sensor parameters for photogrammetry**

Dering, G. M., Micklethwaite, S., Thiele, S. T., Vollgger, S. A., & Cruden, A. R. (2019). Review of drones, photogrammetry and emerging sensor technology for the study of dykes: Best practices and future potential. *Journal of Volcanology and Geothermal Research*, *373*, 148–166. https://doi.org/10.1016/j.jvolgeores.2019.01.018
***A comprehensive paper about the use of SfM for the study of dykes**

Federman, A., Santana Quintero, M., Kretz, S., Gregg, J., Lengies, M., Ouimet, C., & Laliberte, J. (2017). UAV PHOTGRAMMETRIC WORKFLOWS: A BEST PRACTICE GUIDELINE. *The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*.

Gerke, M., & Przybilla, H. J. (2016). Accuracy analysis of photogrammetric UAV image blocks: Influence of onboard RTK-GNSS and cross flight patterns. *Photogrammetrie, Fernerkundung, Geoinformation*, *2016*(1), 17–30. https://doi.org/10.1127/pfg/2016/0284

Giordan, D., Hayakawa, Y., Nex, F., Remondino, F., & Tarolli, P. (2018). *Review article : the use of remotely piloted aircraft systems (RPASs) for natural hazards monitoring and management*. p.1079–1096.

Iglhaut, J., Cabo, C., Puliti, S., Piermattei, L., O'Connor, J., & Rosette, J. (2019). Structure from Motion Photogrammetry in Forestry: a Review. *Current Forestry Reports*, *5*(3), 155–168. https://doi.org/10.1007/s40725-019-00094-3
***A review of photogrammetry in forestry with extensive list of references applicable to geoscience. Discusses survey design, camera, and settings.**

James, M. R., Chandler, J. H., Eltner, A., Fraser, C., Miller, P. E., Mills, J. P., … Lane, S. N. (2019). *Guidelines on the use of structure-from-motion photogrammetry in geomorphic research*. https://doi.org/10.1002/esp.4637
Great insight about robust reporting methodologies when applying SfM-MVS workflows for geoscience. Written by an researcher highly involved in understanding block deformation caused by image block geometries

James, M. R., Robson, S., Centre, L. E., & Engineering, G. (2014). *Mitigating systematic error in topographic models derived from UAV and ground-based image* *networks*. *1420*(June), 1413–1420. https://doi.org/10.1002/esp.3609

***Comprehensive description of dooming effect and discussing about self-calibration and systematic error.**

Laporte-Fauret, Q., Marieu, V., Castelle, B., Michalet, R., Bujan, S., & Rosebery, D. (2019). Low-Cost UAV for high-resolution and large-scale coastal dune change monitoring using photogrammetry. *Journal of Marine Science and Engineering*, *7*(3). https://doi.org/10.3390/jmse7030063

Meinen, B. U., & Robinson, D. T. (2020). Remote Sensing of Environment Mapping erosion and deposition in an agricultural landscape : Optimization of UAV image acquisition schemes for SfM-MVS. *Remote Sensing of Environment*, *239*. https://doi.org/10.1016/j.rse.2020.111666

Mosbrucker, A. R., Major, J. J., Spicer, K. R., & Pitlick, J. (2017). Camera system considerations for geomorphic applications of SfM photogrammetry. *Journal of Geophysical Research: Earth Surface*, *42*(6), 969–986. https://doi.org/10.1002/esp.4066

***Comprehensive look at SfM-derived DTM providing a synthesis of camera system selection, configuration, acquisition techniques**

Nesbit, P. R., & Hugenholtz, C. H. (2019). Enhancing UAV-SfM 3D model accuracy in high-relief landscapes by incorporating oblique images. *Remote Sensing*, *11*(3), 1–24. https://doi.org/10.3390/rs11030239

***Recent study looking at over 150 scenarios and discussing convergent image geometry, nadir-oblique combinations, as well as various tilt-angles. Touches on the effect of self-calibration.**

Nex, F., & Remondino, F. (2014). *UAV for 3D mapping applications : a review*. 1–15. https://doi.org/10.1007/s12518-013-0120-x

Seker, D. Z. (2020). *INVESTIGATING THE ROLLING SHUTTER EFFECT OF LOW-COST UAV CAMERAS ON PHOTOGRAMMETRIC MAPPING ACCURACY.* (February). Retrieved from research gate.

Smith, M. W., Carrivick, J. L., & Quincey, D. J. (2015). Structure from motion photogrammetry in physical geography. *Progress in Physical Geography*, *40*(2), 247–275. https://doi.org/10.1177/0309133315615805

Thoeni, K., Guccione, D. E., Santise, M., Giacomini, A., Roncella, R., & Forlani, G. (2016). The potential of low-cost rpas for multi-view reconstruction of sub-vertical rock faces. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives*, *41*, 909–916. https://doi.org/10.5194/isprsarchives-XLI-B5-909-2016

Westoby, M. J., Brasington, J., Glasser, N. F., Hambrey, M. J., & Reynolds, J. M. (2012). “Structure-from-Motion” photogrammetry: A low-cost, effective tool for geoscience applications. *Geomorphology*, *179*, 300–314. https://doi.org/10.1016/j.geomorph.2012.08.02