

Cover Sheet

This is a preprint. Please note that it has not yet undergone peer-review and subsequent versions of the manuscript may have different content. It has been written and published here to share experience on virtual outcrop acquisition. This is a rapidly evolving and changing field. We welcome feedback and invite you to contact the authors directly to comment on the manuscript (john.howell@abdn.ac.uk).

Authors

Howell, J.A., Chmielewska, M., Pugsley J., Virtual Outcrop Group, School of Geosciences, University of Aberdeen, UK

Lewis, C., Buckley, S.J., Naumann N., Virtual Outcrop Group, NORCE Norwegian Research Centre, Bergen, Norway

Corresponding author john.howell@abdn.ac.uk

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Acquisition of Data for Building Photogrammetric Virtual Outcrop Models for the Geosciences using Remotely Piloted Vehicles (RPVs)

Howell, J.A¹., Chmielewska, M¹., Lewis, C²., Buckley, S.J²., Naumann, N². and Pugsley J. ¹

¹Virtual Outcrop Group, School of Geosciences, University of Aberdeen, UK

²Virtual Outcrop Group, NORCE Norwegian Research Centre, Bergen, Norway

Corresponding author john.howell@abdn.ac.uk

Abstract

Over the past five years the use of 3D models in the Earth Sciences has become ubiquitous. These models, termed Virtual outcrops, are most commonly generated using Structure from Motion (SfM) photogrammetry, an image-based modelling method that has achieved widespread uptake and utilization. Data for these models is commonly acquired using remotely piloted aerial vehicles (RPVs), commonly called drones. The purpose of this document is to present a basic acquisition methodology, which is based on the workflows used by the authors for the acquisition of over 500 virtual outcrops over the last decade.

This article is part of a series from the editors of V3Geo, which is an online forum for sharing high quality virtual 3D geoscience models. Virtual outcrops submitted to V3Geo are subject to a technical quality control to ensure that data can be reliably utilized by the wider professional and scientific community. This document provides guidelines for the robust acquisition of data which are required to build high quality models suitable for sharing in V3Geo. The document focuses on outcrop selection, mission planning, RPV setup, data acquisition and management. Related documents in this series cover data processing and model building.

Background

Virtual outcrops (VOs), also called Digital Outcrop Models (DOMs) or Virtual Outcrop Models (VOMs), are photorealistic computer models of geological outcrops, such as cliffs, quarry faces or wave cut platforms (Bellian et al. 2005; Pringle et al. 2006; Enge et al. 2007). Early virtual outcrops were typically collected using terrestrial laser scanners, commonly termed lidar (Bellian et al. 2005; Buckley et al. 2008a), and while this method has proved to be very effective, it was not widely adopted across the geoscience community because of limitations associated with the costs, required expertise and portability of the equipment. Over the last decade, low cost, easy to operate, remotely piloted vehicles (RPVs, also called unmanned/unpiloted aerial vehicles; UAVs; or simply drones) with high quality digital cameras started to become widely available. The development of RPV camera platforms circumvented limitations with terrestrial lidar, or ground based photogrammetry where camera images were collected from the ground, and therefore obliquely to high outcrops with frequent holes caused by shadowing (Buckley et al., 2008b). Mounting the camera on a drone, as for earlier work using helicopters (e.g. Buckley et al., 2008b; Eide et al. 2014), allows the imagery to be collected close to normal to the topography and improve data coverage and model completeness.

The development of RPVs corresponded with the slightly earlier emergence of SfM (Structure from Motion), a branch of photogrammetry incorporating computer vision concepts which allows 3D models to be built from overlapping photos (Westoby et al. 2012; Micheletti et al 2015). Whilst photogrammetry has been around for over 100 years, SfM allows models of complex shapes and geometries to be generated relatively quickly, from standard photographs, without specialist calibrated cameras or high-end computing equipment. The emergence of several softwares that are relatively cheap (or even free) and easy to use, allowed this method

to reach a wider audience. SfM was initially combined with lidar to produce better models (e.g. Alfarhan et al. 2008; Buckley et al. 2010) before becoming a robust, stand-alone methodology for capturing outcrops.

The methods were rapidly adopted by the structural geology community (Vasuki et al. 2014; Bemis et al. 2014) and in clastic sedimentology (e.g. Buckley et al. 2014, Chesley et al. 2017). They also appeared in other branches of earth sciences such as fluvial geomorphology (Flener et al. 2013), glaciology (Westoby et al. 2015), mining (Tong et al 2015); studying carbonates (Madjid et al 2018), mapping igneous bodies (Kasprzak 2018), thermally mapping active volcanos (Wakeford et al 2019) and multiple other applications. Together, the emergence of RPVs and SfM have resulted in the democratization of virtual outcrops, such that their application is now widespread across the geosciences.

This widespread availability of models has also been facilitated by the development of software to manipulate and interpret the models (such as LIME, Buckley et al. 2019) and databases to store, share and serve models from the cloud e.g. V3Geo, Buckley et al. preprint in review, see also Nesbitt et al., 2020). Although advances in photogrammetry, digital cameras and RPV platforms have greatly simplified the process of acquiring and processing image sets into 3D models, best practice for obtaining high quality and reliable datasets has not yet standardized. The current document therefore focuses on the workflow and procedure for using a RPV to acquire data that can be used to build 3D models in geoscience. As an aid to furthering the adoption and quality of 3D models produced by the geoscience community, we convey practical data acquisition using RPVs, which is reflected in the contribution's inherently personal style.

Choice of RPV

There is a wide range of RPVs available on the market, with a spectrum of features and pricings covering hobbyists through to professional and scientific niches. Whilst high end RPVs which can carry full-frame single lens reflex (SLR) cameras may be necessary in certain cases, most people starting out in virtual outcrop modelling will probably do so with something like the DJI Mavic or DJI Phantom 4. Either of these, with some additional equipment will cost less than £2000. Older models can be picked up for a few hundred pounds and can also produce excellent results. Other makes of RPV are also available such as Parrot, Autel Robotics, Yuneec and more, but the DJI models are, at least at the time of writing, the most widely adopted systems and a good choice for beginners. Fixed wing drones have also been used to good effect in some studies (e.g. Chesley et al., 2017) and they have the advantage of covering large areas rapidly. However, they are limited by having only a nadir (down-facing) camera, are commonly expensive and require mission planning and execution which is not always ideal for fieldwork. While they have clear application, especially for horizontal outcrops, they are seen as a specialist application and outside the main scope of this document.

Although this guide focusses on DJI RPVs, much of the advice is be portable to any brand. The basic requirements for a RPV for photogrammetric modelling of geological outcrops are:

1. The RPV can be piloted manually with a live camera feed.
2. The RPV should be stable in the wind and have satellite (e.g. Global Positioning System; GPS) assisted positioning – some much cheaper units are mainly suitable for flying indoors and lack this.
3. The RPV should have a range of at least 500 m. The max distance for line of sight flying in most countries is 500 m, but the unit should be able to achieve this comfortably.
4. The camera should be of good quality with a range of controls (speed, aperture, etc). The DJI Phantom 4 Pro and Mavic Pro 2 have a 20mb 1-inch sensor that produces excellent results. Good results can also be obtained from the slightly smaller, 12mb sensor on the smaller Mavics and older Phantoms.
5. The camera needs a timelapse function (intervalometer) which allows you to take photos at preset intervals (normally 3 to 5 seconds).

6. The camera needs to be linked to the navigation system, such that the position of the RPV is recorded when each photo is taken.



*Figure 1 – Flying an RPV in the field, mapping shallow marine deposits of the Ferron Sandstone in Utah.
(Photo by Ernest Schwarz with permission)*

Flying and legal aspects

This document is not intended to replace proper flight training and is intended as a guide only. Regulations vary from country to country and even site to site. Reading this is no substitute for learning to fly and familiarizing yourself with local laws and regulations.

Before attempting to collect any virtual outcrop data, LEARN TO FLY. Do not assume that automated mapping software will be available to do it for you. Automated flight planning and flying is designed for classical nadir (downward-looking) topographic applications, where the imaging sensor is flown in a predictable pattern at a (more or less) constant altitude. This setup can be acceptable for less rugose terrain, and for many environmental or mapping applications, but is not appropriate for near-vertical imaging scenarios such as mapping complex cliff lines. In our experience the software does not work well for most outcrops that include a vertical component. Most importantly, even if you are using automated mapping software you still need to be able to take control of the aircraft if anything goes wrong. Learning to fly may involve attending a course, it will also involve spending time in a wide-open space, mastering the aircraft. Modern RPVs are surprisingly easy to fly but you should not be tempted to assume that means you do not need to know how they work. Things can go wrong very quickly and when they do, you are responsible. If you don't attend a formal training course, we would suggest getting instruction from an experienced or qualified pilot and then spending several days mastering the controls both with and without the GPS stabilization. Flying should be second nature.

The requirements for licenses and permits to fly vary from country to country, from location to location within countries and between institutions. Any discussion on this is beyond the scope of this document, however

you are responsible to make sure that you have permission to fly and to collect data at the outcrops you plan to study. As a minimum you should

1. Follow the drone regulations for the territory you are operating in (Fig 2, example from UK).
2. A basic summary of typical regulations is to fly no further than 500 m from the pilot, within line of sight, no higher than 120 m and not within 50 m of people or built up areas.
3. Have permission from the landowner of the location you intend to fly from.
4. Understand airspace designation and check what it is for your location (there are numerous apps and website for this such DroneAssist in the UK or Airmap in the USA).
5. Do a visual, site specific safety assessment at the locality.
6. Check the short-term weather forecast, most drones will give high wind speed warnings at 7 m/s and should not be flown above 10 m/s (Force 5) or if it is raining.
7. Given that the RPV can fly for c. 30 mins at up to 50 km/h then you should have the contact details for any airports, local police etc. within a 25 km radius in case of a fly away. If a fly away occurs, take a detailed measurement of the direction it was last seen heading and the remaining battery life. Then immediately call the airport or if it is over a built-up area, the local police. Do not wait until the RPV has gone rogue before trying to find this information.

Peacock and Corke (2020) provide a useful overview of RPV safety considerations, although laws have already changed since that paper was published and will continue to change.

Remember, it is your responsibility to know how to operate an RPV safely and legally and to have permissions and insurance in place before you take off.

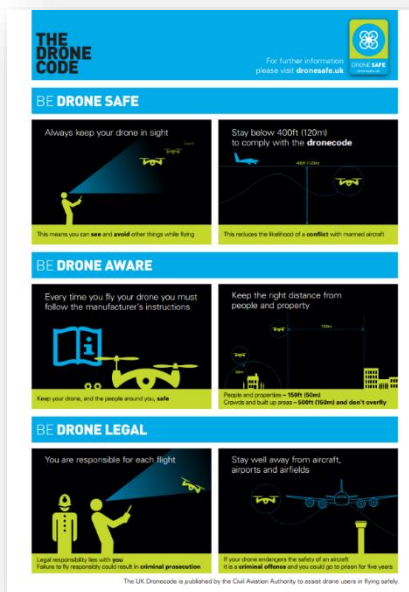


Figure 2 – The Drone Code for the UK, similar documents exist for many other countries.

Choice of outcrop

The best outcrop is one that you want to study. Virtual outcrops are generally a supplement to traditional fieldwork and therefore the first requirement for a suitable outcrop is for it to be geologically interesting. It is possible to produce virtual outcrops that are 10's km long but a good size to start with is up to 1 km long and up to 30 m high (Fig 3). Once an outcrop has been selected the next critical aspect is that it is safe to fly a RPV

there and that you have the required permissions (see above). Many outcrops may sit in restricted airspace, on private land, close to built-up areas, or near industrial areas or busy roads.

As stated above a simple outcrop will be a vertical or near vertical cliff line, less than 1 km long and around 30 m high (e.g. Fig 3). More complex examples might be larger, or have increased irregularity which improves the 3D nature of the data collected but also increases the challenges associated with flying. Operating in narrow canyons is especially difficult as the RPV will typically be flying sideways and there is a risk of colliding with the cliff. Power-lines are a serious problem as they are hard to see and often not detected by the RPVs collision avoidance system. In challenging settings, a spotter can be extremely useful.

Larger outcrops are typically flown in segments and pieced together, either when the models are built, or they can be collected as separate models and combined later. It is useful to start with a small and compact outcrop for your first flights and build up to more demanding localities.

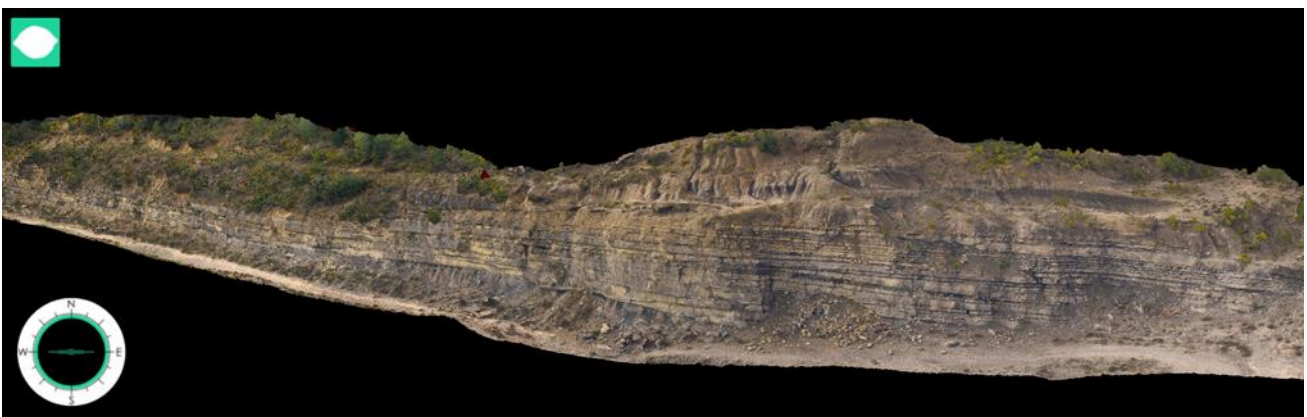


Figure 3 – Virtual outcrop of the Ainsa Quarry in Spain which is typical for a small to mid-sized virtual outcrop.

Survey Design

Once you have decided to collect a virtual outcrop and ensured it can be done legally and safely, the next stage is to design the survey. This can be done in the lab before going out (for nadir mapping) or in the field. The key consideration is the purpose the data are being collected for. This has significant impact on the size of the virtual outcrop (area covered) and the anticipated resolution. Resolution is a function of the sensor resolution in the camera and how close to the cliff the photographs are taken. Figure 4 shows the pixel size (ground sampling distance; GSD) with respect to different camera distance. A more detailed estimate can be obtained using the online app at <https://www.propelleraero.com/gsd-calculator/>. This is only a guide because unless the surface is completely planar, you will not be able to maintain an exact distance and the GSD will vary as a function of terrain complexity. As a rule of thumb being up to 30 m from the outcrop gives satisfactory results (less than 1cm per pixel). The Phantom 4 Pro and Mavic 2 have a 94° lens which is equivalent to 20mm on a standard SLR. Practically, this means that the height of the image (in landscape format) is approximately equal to the distance of the camera from the cliffs.

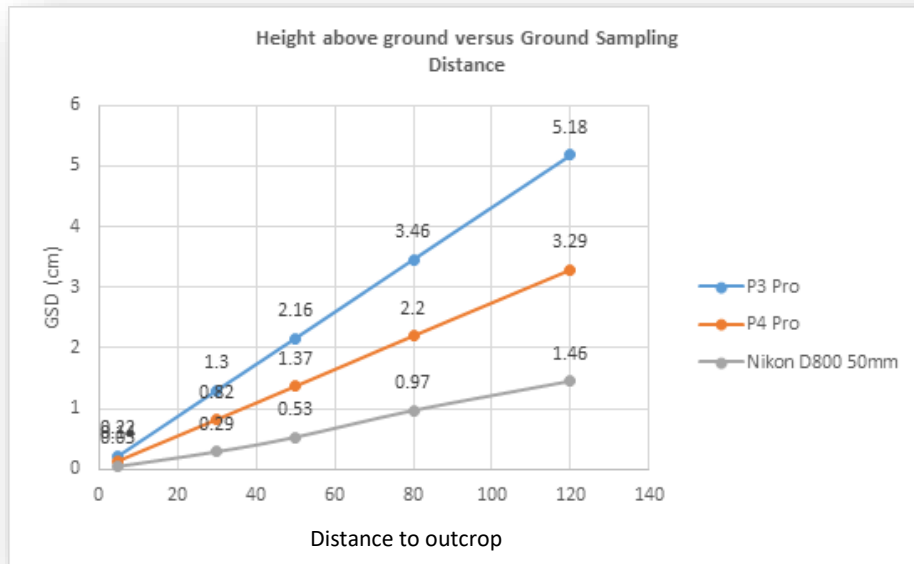


Figure 4. Ground sampling distance vs distance to outcrop, determining the resolution of the final virtual outcrop model.

Other considerations are outcrop orientation and lighting. A smooth outcrop in direct sunlight will give excellent results, but outcrops are rarely smooth and harsh light will often result in shadows in the model. The optimal conditions are a bright overcast day where the clouds act as a diffuser and the light is evenly distributed. The worst-case scenario is if the sun is directly behind or just above the cliffs (e.g. trying to collect data from a west facing cliff in the morning). This results in the detail of the cliff being in shadow, the camera struggling to set exposure (see below), focus problems and flare (bright coronas around the cliff edges). While we may be forced to collect data in these conditions, it is best avoided if possible and some prior planning can make a big difference. Useful apps include www.suncalc.net which has an excellent tool that shows the position of the sun at a locality on a specific date and time (Fig 5). You may decide to collect data from different parts of the outcrop at different times of day to optimize the lighting.



Figure 5. Using www.suncalc.net to plan RPV flights.

Manual vs automated flying

There are numerous apps and survey design software packages that are commonly used by the surveying industry to automate the flight, so that the survey is planned in the lab and then executed in the field with a simple command. Various authors, including Peacock and Corke (2020) strongly advocate for using these apps. In our experience this is neither optimal nor practical for all but the simplest outcrops for reasons outlined below.

We have experimented with almost all survey planning apps and have not found any that can satisfactorily map complex outcrops. The key problem is that they are typically designed for mapping planar surfaces (nadir mapping) or relatively simple structures such as buildings. Outcrops are generally highly irregular and do not lend themselves to this acquisition configuration. Even the more advanced tools that allow 3D way-point planning are typically not suitable as they require a high-resolution terrain model which is rarely available at the planning stage. Acquiring a terrain model is commonly part of why you are doing the survey! Our experience to date is that it is better to plan the survey but to fly manually for the actual acquisition. This may change in the future as better automated systems become available. The only exception to this is when mapping planar surfaces, such as wave cut platforms. In these cases, the automated algorithms will do an excellent job.

Field Equipment

In addition to an RPV, and traditional field equipment you will typically need the following:

1. Spare batteries. A battery normally lasts 20-30 minutes. It is recommended to take between 3 and 10 to the field depending on how much flying is anticipated;
2. Selection of memory cards. In addition to having enough storage space, its often useful to change cards after flights to prevent catastrophic loss of data collected earlier in the day in the event of a crash or flyaway;
3. Spare propellers;
4. A tablet or phone to operate the RPV. Recommended to take both and keep the phone as a back-up. Ensure that you have cables for each. Software (e.g. the DJI app) should be up to date on both;
5. A car charger or inverter in the vehicle can be useful for battery charging while in the field;
6. Pair of binoculars for spotting;
7. Maps of the surrounding area (can be digital but should be downloaded to tablet/phone);
8. Key contact numbers for landowner and emergency services;
9. Permission for aerial work (in the UK), operation manual, and/or other documentation conforming to local regulations;
10. Anemometer (measures wind speed) can also be useful. It is not advisable to fly in wind speeds over 10m/s;
11. Differential GPS and targets if ground control points (GCPs) are to be included in the acquisition.

At the outcrop

Once you arrive at the outcrop you should recheck the safety aspects. Recheck the weather and the conditions and also check for people, animals, traffic, power lines etc. Review where you plan to fly and where you plan to take off. Can you see the whole of the outcrop? Then check for possible hazards that did not come up in the original safety review and adjust the plan accordingly. As discussed above, full instructions for the safe operation of RPVs is beyond the scope of this document and you should seek proper training and instruction.

When you have decided on your take off and landing spot, you should lay out your kit and set up the RPV and the controller. This will normally involve putting on the propellers, removing the gimbal mount protector and starting the RPV. Ensure it is on a flat surface with plenty of space around it. Starting the RPV early will allow the GPS navigation system time to find satellites, if you have travelled a significant distance since the last flight, this may take a few minutes. If ground control points (GCPs) are being used (see discussion below) they will need to be set out before the survey starts. Their position can be surveyed at any point before, during or after the operation.

Once the RPV is set up, assemble the controller and add the phone/tablet. If you are using a phone it can be worth switching off the phone and other alerts so that you are not disturbed during the flight. Do not switch to airplane mode, because, if data coverage is available then allowing it to access maps can be useful. If you are using a tablet or a phone with no coverage, accessing the maps of the area you plan to fly in before you go there will result in the maps/satellite images being cached locally and available during the flights. This is not essential but can be useful.

Turn on the DJI app and allow it to connect to the RPV. Before you fly it should have a green, Ready to Go (GPS) bar at the top left. Do not fly without this unless you are highly experienced. This should correspond with more than 10 satellites. Check the battery level – typically a flight should only start with a full battery.

At this point you should also set up the return to home altitude (RTH), contrary to its definition in the DJI app, this is a height rather than an altitude. RTH will bring the RPV home if communication is lost between the controller and the drone. Once the signal is lost the RPV will fly up to the specified height and then back to the home point. It is essential that the height is high enough that it will clear obstacles on its route home. It is best to set it each time, rather than just setting it at a very high number and forgetting about it because there is a chance of running out of battery on the way home and then a forced landing will occur.

Setting up the camera

Camera set up is one of the most important aspects of building a good 3D model. Before each flight, select the camera control icon and then the camera icon. Set the White Balance to manual, either sunny or cloudy depending on conditions. Do not leave on auto (AWB), because it can vary significantly during a survey and create photos with different colour casts. Then select the photo icon and select Timed Shot. Three seconds is a good guideline though the value will depend on how quickly you are flying. Taking more pictures than you subsequently use in the eventual modelling is better than having gaps. With older versions of the app, this setting is not remembered at shut down and must be reselected for each flight.

You may wish to switch the image file format to either RAW or JPG. In the majority of cases we would recommend JPG. RAW files are much larger and need to be processed before they can be used. You will be taking hundreds or even thousands of images and in most cases shooting RAW simply isn't required. The principal exception to this is when the lighting on the outcrop is challenging and potentially changing. In that case it may be useful to have RAW images that have greater scope for later manipulation (adjusting exposure stops). Generally however, and for your first models, stick with JPGs.

The next stage is to open the exposure menu in the app and set up the camera. As with any photography there is a tradeoff between aperture (which controls depth of field) and shutter speed (which stops the images being blurry). If the lighting is relatively uniform and the sun is not behind the cliff you are trying to acquire data from, Auto exposure can work fine. However, the modelling generally works better with a small aperture (high F – number and high depth of field). If the outcrop is reasonably well illuminated select Aperture Priority and select F/11 or higher. The trade off is that this will reduce the shutter speed. As the RPV is moving while the photos are being taken you want a relatively fast shutter speed (preferably 1/250 or faster). The easiest way to determine what the likely speed with your selected aperture will be, take the RPV in your hand and point

the camera at the darkest part of the outcrop and check the speed. This is a form of spot metering. You can then adjust the ISO to help compensate. Ideally the ISO should be as low as possible to minimize sensor noise. Up to 800 or even 1600 is still acceptable using DJI Phantom 4 cameras.

An alternative, if the outcrops are badly shadowed or back lit, is to use full manual mode. For this, point the camera at the outcrop and move it around, watching the metering. The metering will commonly average the scene but you are not interested in the sky or anything other than the outcrop, so try and get a position where the geology fills the frame and note the values there. These can then be set and fixed. This approach is more challenging to get right and you may end up with a bunch of photos that are too dark or too light. Initially we would suggest only doing this if you really know what you are doing.

Once the camera is set up you are ready to take off and acquire data.

Flight Pattern

The optimal flight pattern for acquiring data is to make three passes along any given section of the outcrop. The RPV is pointed looking directly at the cliff and flown sideways. As you fly sideways you will see when the photos are taken from the live view. Adjust the speed of flight so that there is at least 70% overlap between adjacent pictures. If the outcrop curves in a concave fashion, stop and slowly rotate the RPV taking overlapping photos. If the outcrop has a curved outline, fly slowly around to ensure good coverage. Don't be afraid to take too many photos, they can be sorted during the processing phase of the workflow.

The first pass along the cliff line will be fairly low with the camera looking horizontally to 10° tilted (Fig 6). Try to maintain a near-uniform distance from the cliff as this will control the final model resolution. Once the first pass is complete, send the RPV up and look down on the cliff at 30-40°. Make a second pass of the same section. The flight line on the map on the app will help to ensure that you are imaging the same section of cliff. Finally ascend further and tilt the camera to 80° and make a third pass; each photo should have >70% overlap, as on the previous passes (Fig 6). If the outcrop locality is very high, this strategy can be adapted by inserting extra flight lines.

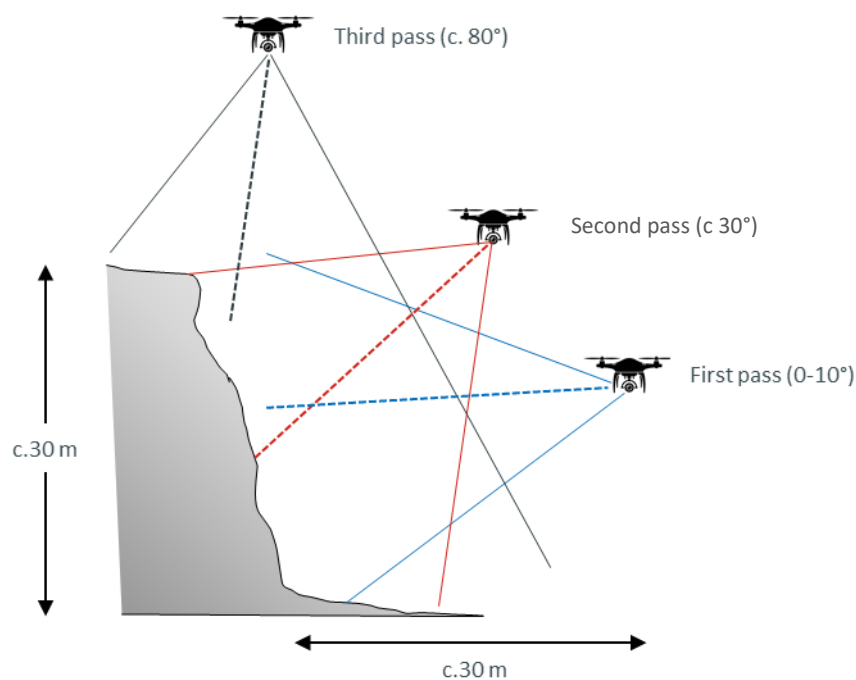


Figure 6. Fly three transects to ensure complete coverage of the cliff section.

The RPV regulations in most countries allow you to fly 500 m from your take off spot, as long as line of sight is maintained. Using this it should be possible to collect data from 1 km of cliff section. To capture longer cliff lines, simply move along the cliff and capture further sections from different take off sites. It is useful to have overlap between flights for model registration purposes. If you leave the controller switched on the map will retain previous flights so you can track progress. We also screen grab the view in the tablet as a record of the achieved flight status.

Higher cliffs are more challenging, but we follow the same procedure of three flight passes per section (10°, 40°, 80°). It is important to be organized and remember/check what you have done. Often you can fly by the cliff at the same height twice, once looking horizontal and once looking down at 40°. This is very useful for giving context around the outcrop area. We suggest that you start with smaller outcrops and work up to more complex sites.

Mapping planar surfaces, such as wave cut platforms does not require 3 passes. In this case you need to fly a grid. This can easily be done with a mission planning app. If you decide to do it manually the map function is extremely useful. First fly around the perimeter of the area you want to record. Then move in from one of the sides, until you achieve a view with a 70% overlap. Then fly a straight line. Then move sideways again by the same amount and repeat until the box is filled. If there are any vertical ledges or shelves in the view then flying some passes looking at 40° will improve the model.

Once you have finished mapping, overview photos taken from further back which capture the whole outcrop can be useful, both as reference in the model building process and as thumbnails for the models when they are loaded to V3Geo.

Ground Control Points (GCP)

The RPV contains a satellite navigation system and will record its estimated position each time it takes a photo. These data are stored in the metadata of the photograph (EXIF) and they are used in the model building process, initially to estimate the position of the camera during processing and secondly to estimate the location of the model in absolute coordinates once it has been built. The internal GPS of a standard RPV such as a Phantom 4 Pro or Mavic 2 Pro with good satellite coverage and a clear view of the sky will typically have a positional error of less than 5m. Phantoms and other systems with real time differential GPS system are available (e.g. Phantom 4RTK) however these are considerably more expensive and their current software configuration means that they are not well suited to mapping outcrops.

The positional errors will impact the accuracy and precision of the model. It is useful to understand the distinction between accuracy and precision (Fig 7). Accuracy refers to how close the estimate of position is to the true position. Precision refers to how consistent a series of successive measurements are to one another. In the context of virtual outcrops both accuracy and precision affect the processed model. The accuracy will determine how close points in the model are to their real-world coordinates and will affect measurements or correlations made between unconnected outcrop sections. Precision will affect the internal structure of the model and how reliable measurements such as bed thickness are. In the majority of cases, virtual outcrops generated based on the RPV's internal GPS will have a high degree of precision, assuming a strong network of photo orientations and overlap, but relatively low accuracy, such that the actual location of the model can be significantly out from its true location.

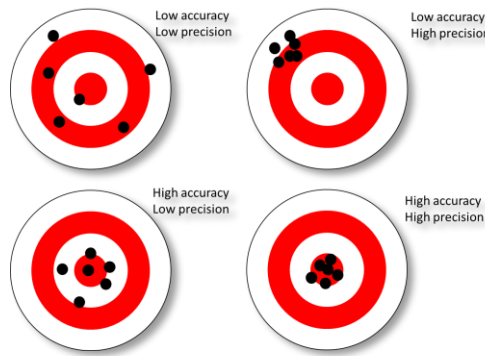


Figure 7. Schematic targets illustrating the distinction between accuracy and precision.

In many cases this is not critical. If you are interested in viewing or even measuring features within the outcrop, having it located with m or cm accuracy may not be necessary. However, if you plan to combine VOs with other georeferenced data, or combine multiple VOs, or use the VO to plan engineering activities then it will be necessary to improve the accuracy. This is typically achieved using Ground Control Points (GCP).

Ground control points are a series of points within the photo set that have been accurately measured, typically using a differential GPS (dGPS) which has accuracy in the order of 1cm. The principle of dGPS is based on comparing the estimated position from one receiver (the rover), with the measured position of a fixed base station. In the rover unit there are two main uncertainties, the movement of the unit and the drift of the satellite position, called pseudorange errors. As the base station is static, it enables shorter-term positioning errors, caused for example by atmospheric and satellite drift, and uniform over moderately large areas, to be removed from the rover unit. This can be either performed during post-processing, or by broadcasting the signals in real-time. Real Time Kinematic (RTK) systems, in which the base station and rover communicate by radio signal provide high (cm) accuracy. The base station may be installed by the user at the start of the survey although in many countries there is now a network of base stations from which corrections can be obtained, either by download at the end of day, or real-time through a mobile phone SIM card (where coverage exists).

For a typical survey at least 10 GCPs should be placed around the study area. These should be located where they will be visible in the model. They do not need to be laid out in a grid but they should be evenly distributed across the area, ideally around the edges of the area. GCPs should be large enough to be identifiable within the photographs and of a colour distinct to the ground that is being surveyed. Several of the GCPs can be reserved as checkpoints for assessing model accuracy (i.e. excluding them from the photogrammetric adjustment stage and instead using them to compare the measured versus computed coordinates). Professional targets can be purchased from survey suppliers, but they can also be easily made. For example, we typically use red plastic picnic plates as they are cheap, robust and easy to find in the images.

Once the targets are placed on the ground the position should be measured using the dGPS. GCPs need to be numbered and the data recorded in a systematic fashion. After the flight is completed, they are collected to be used in the next flight. If a survey includes multiple overlapping flights, it can help to leave some of the GCPs in the overlap area. Once the location of the GCPs is recorded and calculated, the data will be used in the processing.

Adding GCPs to the data acquisition workflow is time consuming and expensive. The process described above will typically at least double the time taken for each flight. It also requires additional equipment to be bought or rented. It also adds significantly to the amount of kit that needs to be taken to the field and the number of batteries that need to be charged each night. Whilst the use of GCPs is often desirable and model accuracy can be very important, there are many cases when it is not necessary, especially since the model precision is

normally very good. Furthermore, it is relatively easy to transform virtual outcrops after they are built in order to match with other data or known measured positions (e.g. using digital elevation data or aerial photographs, if available at high enough resolution). Ultimately the decision to use GCPs will depend on the user and on the purpose of the survey.

Download and Organize Data

Following a flight mission, back at base, you should download the imagery and organize them into folders by outcrop. Do not be tempted to wait until the memory card is full. A typical flight will involve 400+ photographs and larger models may involve 10+ flights. It is easy to lose track, and as long as the data is only saved on the memory card, there is the risk of losing those data in the event of a card failure or RPV incident. Make it a routine to download all data and back it up while charging batteries in the evening. It is also useful to keep a written record of what flights were made in your notebook or fieldwork log. Regulations may demand this.

Once the data have been acquired and safely stored, the next stage of the workflow is processing the image sets to generate 3D virtual outcrop models (Buckley et al., preprint in review).

Summary

Virtual outcrops have become a routine tool in the geoscientists' toolbox. They have a wide variety of applications through research, teaching, outreach and beyond. Virtual field trips have become a key part of geoscience teaching during the COVID-19 pandemic and associated lockdown, and beyond. RPVs and SfM (drones and photogrammetry) have become the main tool for the collection of virtual outcrops. Our research group has collected over 600 virtual outcrops, many of which have been shared on V3Geo (v3geo.com; Buckley et al., preprint in review). The purpose of this document has been to provide a simple, step-by-step guide to the acquisition of data using RPVs. It is not intended as a review of this rapidly expanding field of research, Harrauld et al. (2021) provide an excellent overview although the science is moving very quickly. We have attempted to outline the steps we go through when acquiring the models (typically with DJI drones) in a way that will allow new adopters to get started with the virtual outcrop acquisition. There is significantly more to the process and there are unique challenges associated with every outcrop, but this document should serve as a starting point and allow new users to benefit from our experience. The goal of V3Geo is to become a community resource that houses high quality digital versions of most of the world's outcrops. Please consider contributing to this effort using the project website (<https://v3geo.com>).

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