The Use of Unmanned Aerial Vehicles (UAV's) to Monitor Industrial Sites and Reclamation: Example of Oil and Gas Well Sites.

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Executive Summary

A project was designed to acquire, and process, high resolution data collected with multiple sensors tethered to a UAV. The intent was to collect data over a number of abandoned well sites in northern British Columbia. We chose 5 sites over which we collected data. The sensors used for the project included an RGB camera intended for high resolution colour imagery, a Light Detection and Ranging (LiDAR) system, and an imaging spectrometer. The data were processed so as to yield a high resolution (between 1 and 2 cm) orthophotomosaic and 3-dimensional point cloud from the RGB photographs; a 3-dimensional point cloud from the LiDAR data, and a vegetation classification from the imaging spectroscopy data. A copy of the processed data is included with this report. These data are georeferenced so that they can be ingested into a spatially registered database for integration into further and future analysis.

The data were collected in early September. We initiated the project later than we had originally hoped due to delays in getting the necessary contractual paperwork between BCOGRIS and the University of Victoria in place. As such the weather conditions were marginal for data collection, and so we did not collect a complete package for each of the chosen 5 sites. One of the sites had a complete coverage, but due to strong winds the imaging spectrometer data could not be orthocorrected to the standards that we need for integration with other data. Another site had photography and LiDAR while the rest had photography only.

Other than the weather the main constraints on this approach to gathering high resolution spatial information is regulatory. At present we are restricted to flying within line of sight. In other words, the maximum distance that we can fly with an unobstructed view is with a 1 km radius flight plan. The current technology available with the more popular off the shelf systems allows us to fly up to 5 Km from the controller. As with the technological aspects, this will change and regulations will allow for flights beyond the line of sight.

The advantages for this approach to data collection is that we can quickly and inexpensively collect spatially contiguous imagery over an area of interest, and that we can therefore create archival data for costs that are much lower than with more traditional surveys.

Acknowledgements

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Introduction

Miniaturization is one of the most prevalent processes affecting our current work flow. All aspects of our professional and private lives are being affected by this process. Most notably, miniaturization in the areas of electronics and computerization has revolutionized our everyday work flows, and lives in general.

Nowhere is this more apparent than in the field of Geomatics where a miniaturization of electronics has led to a revolution in the collection of high quality data (both spatial and spectral). The advent of "pro-sumer" grade instrumentation in the form of RTK (real-time-kinematic) GPS chips, for example, has led to the development of highly precise and accurate microprocessor chip-based Inertial Navigation Systems (INS). This allows us to position a sensing platform with a high degree of precision. Other developments related to miniaturization envelop imaging and data collection with an increasing array of devices with high signal to noise ratios (S/N) and high spatial and spectral resolutions. These developments coupled with available, low cost platforms such as unmanned aerial vehicles (UAV's), have permitted an explosion of remote sensing systems that are available to the general public as well as more sophisticated users.

This report will focus on a review of some of these platforms and sensors and provide examples of data collection over some well sites in north eastern British Columbia.

UAV Platforms

A large number of unmanned airborne vehicles have been introduced in the last few years. These vary in size, design, payload capacity and duration. In addition to the platform itself there has also been considerable progress in the design and implementation of command and control software. These developments are being made available at the consumer level of platform so that costs are also becoming very competitive. For the remainder of this report I will focus on higher end consumer-grade platforms, commonly referred to as "pro-sumer" grade.

There are two basic types of platforms that are available for use for data acquisition dedicated to geomatics database generation. These include fixed-wing and rotary. Fixed-wing platforms are commonly used in photogrammetric surveys where relatively large areas are imaged using either traditional RGB (red-green-blue) photography for orthomosaicing or vertical point cloud generation, or multispectral scanning. Theses platforms are launched either by hand, catapult, or using runways. They typically have a single or multiple electric (or gas) powered engines for propulsion which allow for longer duration flight times[1].

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[1] I will concentrate on electric propulsion systems in this report, although gasoline driven platforms are also available. Platforms that depend on gas-powered propulsion tend to be larger and require more sophisticated handling than the electric powered ones. Also, the internal combustion engine generates a vibration profile that effects some of the image data acquired, beyond our ability to compensate.

There are a number of drawbacks to the use of fixed-wing systems. The first is that they are less maneuverable than those with multiple engine rotary designs. This means that they require a relatively large turning radius at the end of flight lines thereby reducing the time that they have available to operate over the target area. Second is, as mentioned above, that they need “facilities” to take-off and land. This is especially critical in the landing, as a “rough” landing can damage the airframe and/or the sensors. There are a number of ways that the latter issue can be minimized. The first is through the use of a parachute employed from the aircraft that allows for a vertical, soft landing. Second, and more recent, vertical take-off and landing (VTOL) aircraft have been introduced. These aircraft may have wings that rotate to facilitate vertical take-off and landing, or some sort of hybrid fixed wing-rotary propulsion. Finally, the stall speed of these airframes is relatively high, so that sensors (such as imaging spectrometers, for example) may not have the necessary framerates or integrations times, resulting in unacceptably coarse resolution imagery[2]. One notable exception is that most frame-based RGB and MSS cameras have frame rates that yield high resolution images, even with the high forward velocities.

Rotary aircraft, typically in the form of quadcopters and hexacopters have the advantage of high degree of maneuverability and so are very well suited for surveys of smaller irregularly-shaped target areas. They have a small turning radius and so are efficient in capturing these areas. These platforms are also more stable than fixed-wing in that the command and control software uses an onboard INS to monitor and compensate for changes in platform attitude. This is made especially efficient due to the multiple rotors that are positioned around the periphery of the airframe. Finally, these platforms are deigned to operate at slower forward velocities so that a greater range of sensors can be accommodated. The one big disadvantage of this type of platform is that the power consumption is high, so that frequent battery changes may become necessary.

What has not been mentioned above is the payload capacity of the platform. Most fixed-wing and smaller quadcopters have relatively small lift capacities, typically ≤1kg. This will limit the payload to relatively small light weight cameras (RGB, MSS, or Thermal). Many of the larger platforms (such as the DJI Matrice 600) have a higher payload capacity than most of the fixed wing systems, up to 6 kg, so they can lift many of the payload packages available to fly. The tradeoff here is in endurance where the multiengine rotary platforms have shorter flying times between battery changes than do fixed-wing aircraft.

The command and control software available to operate these platforms have become increasingly sophisticated. They will allow for the planning of larger surveys that consume more than a single battery charge so as long as there are charged batteries available the survey can continue. The main limitation on the size of the survey is the users’ ability to process large volumes of data. For many of the processing and data extraction tools we need to acquire

[2] While for traditional, large aircraft, surveys the forward velocity might not seem to be excessive, given that UAV’s are most suitable for relatively small areas, it is desirable to retain the ability to fly low and slow.

images with a high degree of overlap (see Figure 1). This results in a relatively large number of images that need to be processed to achieve a high quality photomosaic and vertical point cloud, for example.

Figure 1. Sample of flight plan with triggering points for aerial photography. A high degree of overlap (side and edge) result in a relatively large number of photographs per project area.

Sensor Payloads.

Miniaturization, has over the past decade, led to a revolution in sensor development. This process has resulted in the development of smaller sensors with higher S/N and lower costs. A variety of sensors are available to be flown on UAV’s. These sensors are evolving in terms of their size, power requirements and capabilities. This means that over the near to midterm future the sensor capabilities will only increase. Table 1 below summaries the payload capacities of UAV’s and the sensors that can effectively be utilized with these platforms.

Payload	RGB Photography **Uses**: orthophoto mosaics, height point clouds	LiDAR **Uses**: Height point clouds	Multispectral **Uses**: vegetation mapping	Hyperspectral **Uses**: vegetation mapping and possible soil contaminants	Broad-band Thermal **Uses**: Soil moisture, shallow infrastructure.	GPR Uses: buried infrastructure, shallow bathymetry	Mid IR (methane tuned) Uses: gas leaks.
Approximate cost	$1000-$5000	$5000-$250,000	≥$5,000	≥$75,000	≥%5000	?	≥$60,000
≤ 2 Kg	Yes	Possibly[1]	Yes	No	Yes	No	No
2≥≤6 Kg	Yes	Yes	Yes	Yes	Yes	No[2]	Yes
> 6 Kg	Yes	Yes	Yes	Yes	Yes	Yes	Yes

[1] There is a new LiDAR that relies on solid state technology that results in a much lighter unit. These MAY be sufficiently small, along with required INS, power supply and acquisition computer to fit onto a smaller payload UAV.

[2] A Ground Penetrating Radar (GPR) has been flown on an identical platform to the one that was used in this project (a maximum payload of 6 Kg), but it is not known whether the battery performance would allow it to be used in a survey with a substantial geographic area.

Table 1 Summary of UAV payload capacities, sensors, uses and approximate costs.

1. *Photographic – RGB cameras.* The most obvious sensor is the consumer-grade RGB camera. This type of sensor has been modified to accept GPS-based triggering commands so that a regularly-spaced frame capture can be initiated and sustained. The frame capture is triggered by waypoints that are positioned based on the forward velocity, light conditions, and overlap requirements. The quality of the resulting image is controlled by external conditions such as platform stability, illumination, and photosensor density and quality. One of the main characteristics of this type of camera is that the sensor arrays are not calibrated, so while we can generate quality images with pixel densities of typically ≥12 megapixels, we cannot apply these images for purposes other than geometric products. Some have modified the camera/sensors to record near infrared (NIR)energy[3]. These modifications result in images that visually represent NIR reflectance, however, these types of cameras *are not calibrated* to record information consistently so they cannot be used for analytical purposes.

2. *Multispectral Sensor (MSS) Cameras*. These cameras are also frame-based with typically a much lower density of sensors so that the resolution is lower than is typical with the dedicated RGB cameras. However, two significant advantages of this type of camera is that the images are composed of 3 or more band sets (see Figure 2 for example), and second, the sensor arrays *are calibrated*, so that we can use the data in spectral analysis, we can compare data from multiple cameras, over multiple time periods.

[3] Most sensor arrays in consumer-grade cameras have sensitivities that extend into the NIR (~900 nanometers (nm)), however the range between ~700 and 900 nm are typically blocked and unavailable for use by the general user. The cameras can be modified to record

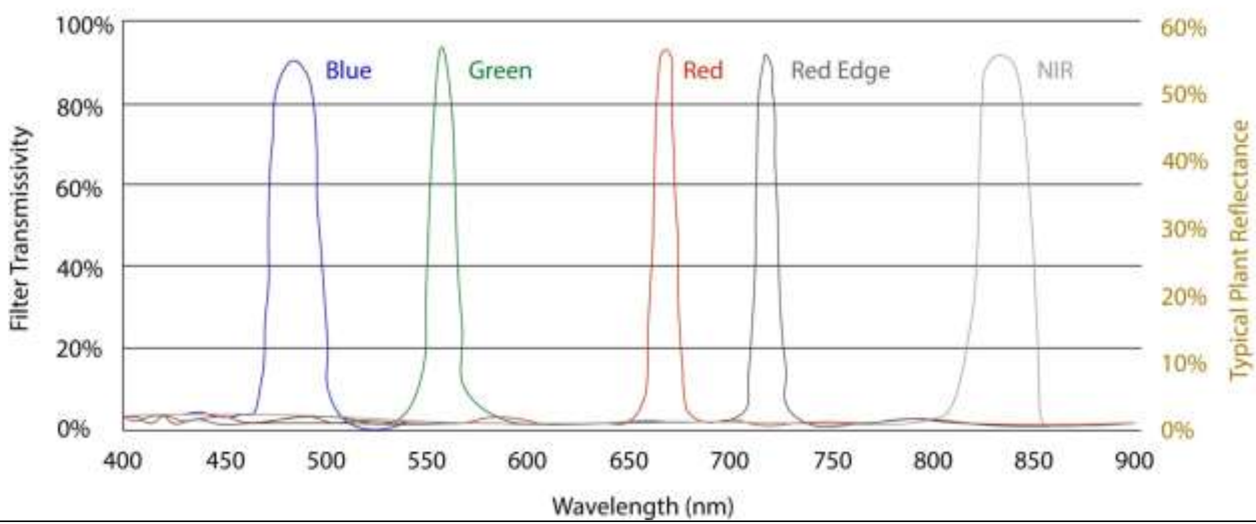

Figure 2: Sample of the band set for a popular (Red Edge from Micasense) MSS camera.

3. *Hyperspectral Cameras*. These cameras are designed to collect a full spectral range of reflected energy from ground targets, and are composed of a series of individual spectrometers that are arranged in a cross-track array. The result when we have a moving target (or the platform is moving relative to the target) is an image that is created from a series of cross-track scans. This type of camera is typically called an imaging spectrometer (IS). The spectrum recorded for each of these spectrometers is represented by a series of contiguous narrow (~1 to 5 nanometers (nm)) bands that range from the visible to NIR (e.g. 400 nm to 1000 nm for V-NIR systems) or to shortwave Infrared (≤ 2500 nm) (see Figure 3). A second advantage is that depending on the spatial resolution of the imagery and the spectral resolution and range, we have the ability to monitor vegetation health, spills (depending on the substance spilled), and different material types. The last two features are best discriminated through the use of the SWIR portion of the spectrum.

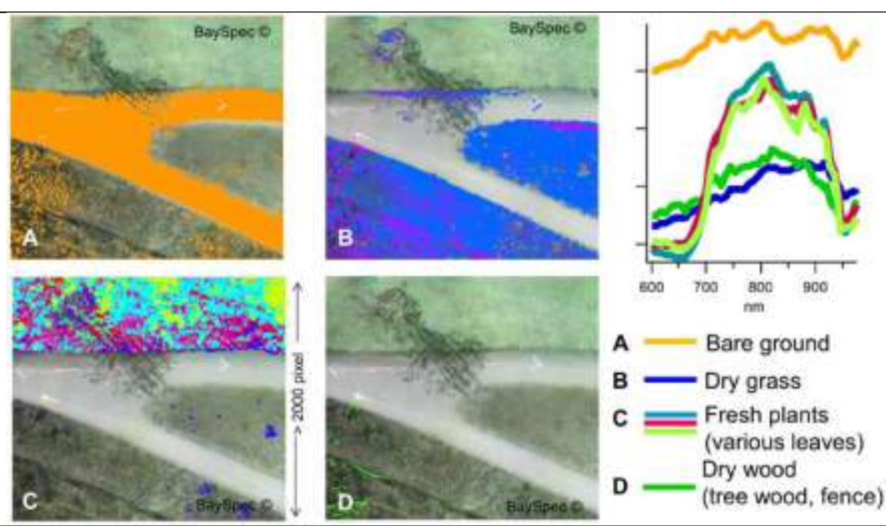

Figure 3 Sample of spectra and representative ground features.

Disadvantages include cost and size. These instruments typically range from $75,000 through $250,000 depending on the spectral range. While the size and weight of the instruments have decreased over time, they are still larger than most systems in use, typically between 1 and 4 Kg., so we are restricted to the type and size of airborne platform that can carry them. Also, the characteristics of the sensors vary and so unless they have very high frame rates then they need to be flown at relatively slow forward velocities, otherwise the spatial sampling distances (that is the resolutions) become unacceptably coarse. One final observation is that the data collected are complex and the level of expertise necessary to process them through to useful products is quite high. As such these sensors have not been widely deployed in surveys.

As mentioned above, IS cameras are primarily scanning systems that build an image line by line. Recently, however, frame-based IS cameras have been released. These capture images in much the same fashion as the regular RGB cameras. As such they can, initially, be processed in much the same way as other frame-based photos using a *Structure from Motion* (SfM) software approach. This will be dealt with later. The cost and weight restrictions on these frame-based systems will be similar to the scanning systems.

4. *Longwave infrared (LWIR) cam*eras. LWIR cameras, otherwise known as thermal cameras, image in the range from 7 or 8 micrometers to 12 micrometers. The most common image in a single band, although there are some larger systems, too large to fly on most common UAV's, that collect hyperspectral thermal data. For most applications, outside of mineralogical identification, a single broad-band system will yield useful information (see Figure 4 below). These systems measure energy emission in the wavelength range of the camera. This emission is typically thought of as the temperature of the object, however, to relate to actual temperatures the values recorded by the sensor must be viewed calibrated to the emissivity of the material of the object that is being imaged.

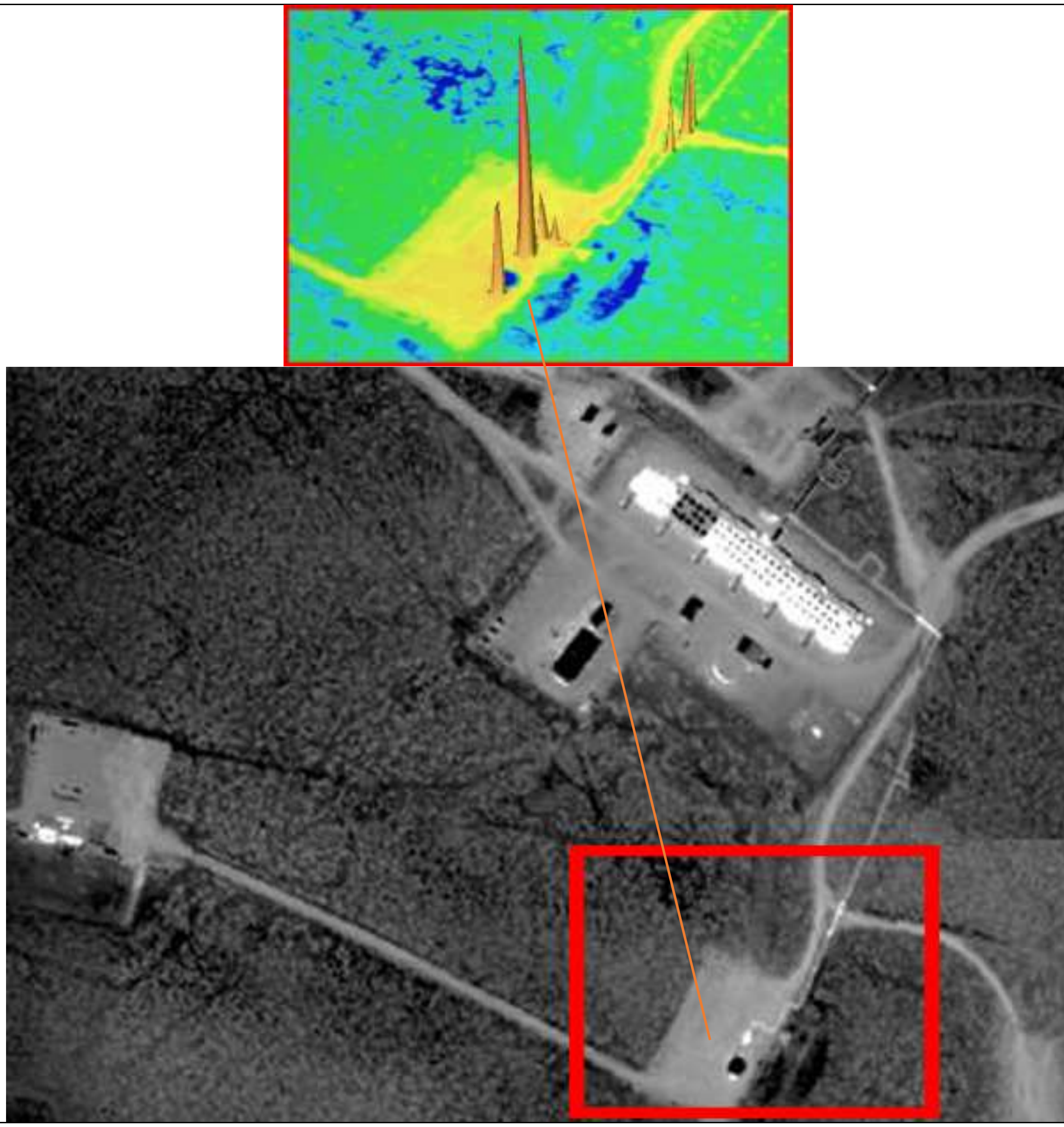

Figure 4 Thermal image of geothermal plant. The inset image shows pipeline with heat "leakage" at various locations. (Source: Terra Remote Sensing/UVic)

5. *Light Detection and Ranging (LiDAR)*: LiDAR sensors have been available and employed in remote sensing work for a number of decades. Typically, these sensors have been large and fitted into fixed-wing and helicopter platforms. They operate on a basis of a very high frequency laser pulse (multiple hundreds of thousand pulses per second) transmission and reception where the time from transmission to reception is recorded and translated into a distance. When downward looking, the height measurements is representative of the top of the reflective surface. A continuous model of these heights is termed a Digital Surface Model (DSM). In most instances the high pulse frequency provides enough penetration of a porous surface to provide a detailed representation of the ground surface underlying the features (e.g. vegetation) on the surface. The resultant elevation model is termed a Digital

Elevation Model (DEM) (see example in Figure 5). If we effectively difference these two models (DSM-DEM) then the result is a terrain-normalized vegetation model or a Canopy Height Model (CHM).

The DSM is most commonly used in our processing thread to orthorectify the hyperspectral data. This allows us to position the hyperspectral pixels with respect to the actual surface and not the ground as is the case when we use a DEM. DEM's are more commonly used to represent the earth surface without vegetation cover (see Figure 5). This allows us to model process such as surface drainage or slope stability (see below).

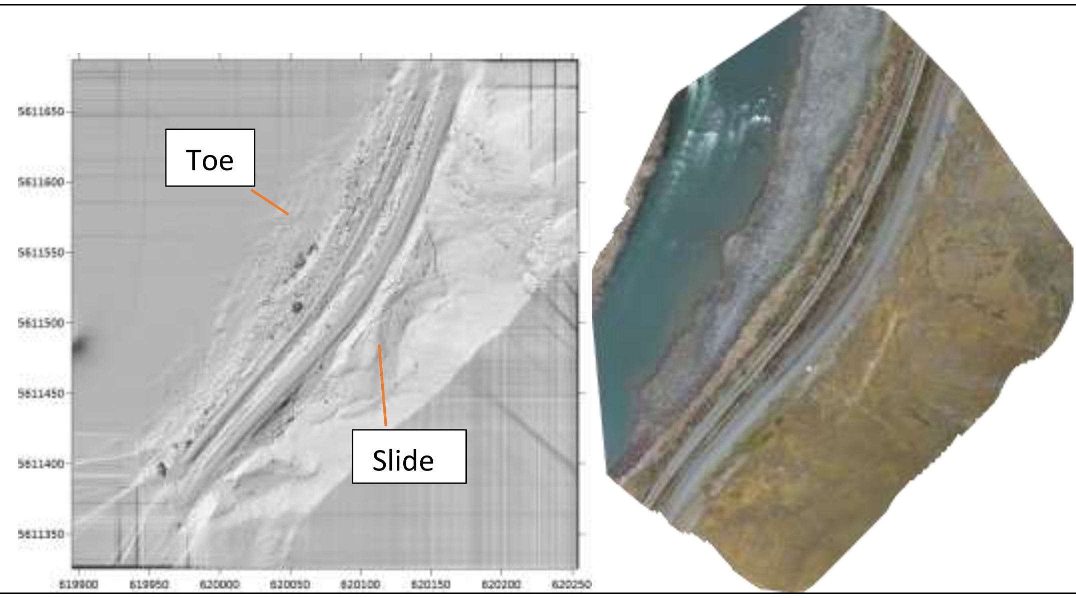

Figure 5. Sample of a DEM of a small landslide and the aerial photo mosaic of the same area. Both images were captured with UAV-based LiDAR and camera. (source: UVic HLRG)

A CHM is normally used to model vegetation biomass, and for larger features, isolated canopy objects so that they can be characterized, either with the hyperspectral or LiDAR data.

Lasers operate as discrete systems where the returning pulse is recorded as one or more "returns", typically *up to* 4, or as full waveform where the returning pulse is recorded as a continuous record of return energy (which represents the stronger reflectors). Post processing of the waveform identifies the maximum peaks in the return energy, and saves those heights as discrete points. Waveform LiDAR systems yield data that have a greater research potential as both the waveform and the discretized points are saved. Less expensive LiDAR systems, such as those used for UAV applications, all record discrete points either as first and last returns, or as a single return. Given the high frequency associated with these systems, however, we can examine the frequency of return by height for relatively small areas/volumes.

Most LiDAR systems are scanning systems with moving parts. Recently, however, solid state lasers have been introduced. These systems have no moving parts, and so do not introduce vibration-related noise, and are lighter, use less power, and less expensive than the more traditional units. It is anticipated that these lasers will cost ≤$500.

As with the other sensors mentioned above LiDAR units have also been downsized. This has mainly been due to the push from the automotive industry in developing proximity sensors for vehicles, and for the development of "driverless" vehicles. The remote sensing community have adopted these sensors for UAV platforms. The relatively light weight (≤1kg) and high frequencies result in sensors that can readily be integrated into UAV platforms. These sensors are also relatively inexpensive, typically less than $20,000, however there are some purposefully built UAV LiDAR sensors that cost around $250,000. The more expensive lasers are true miniatures of the larger versions that are used in large area surveys. They are full waveform systems (see for example the Reigl VUX and MiniVUX). The discrete systems (manufactured by Velodyne and Quanergy for example) are significantly less expensive, typically less than $5,000.

6. *Other sensors.* There are a number of specific sensors that have been developed. For example, a mid-IR camera with a spectral range of 3.2 to 3.4 micrometers has been developed by FLIR. This range is specifically useful to monitor hydrocarbon gases (methane) which have a narrow, but deep, absorption feature in that range.

A second sensor of note is a ground penetrating radar specifically designed for UAV's: (https://www.ugcs.com/en/page/ugcs-for-ground-penetrating-radar-surveys).
This sensor is designed for relatively shallow ground penetration to map soil discontinuities and buried items. It has also been used to map bathymetry in shallow water bodies.

Both of these sensors are of a size, weight, performance, and power requirement to make them suitable as payload for UAV's.

Processing Software

All of the software needed to process the data generated by the sensors mentioned above are available either through commercial vendors or as open source.

1. *Photomosaicing and 3-D point cloud generation from aerial photographs*. There are a number of open-source options for Structure-from-Motion (SfM) software. Also, three primary commercial packages from Pix4D, AgiSoft, and SimActive, are also popular. These all use the concept of image correlation to develop interior orientation, and position the photographs relative to each other. The more correlation points, the better the positioning is. When complete the software applies the parallax formula to the offset between common points, relative to the photo center, to determine the heights above an arbitrary datum.

Once complete the output (orthophoto mosaic and point cloud) are positioned in absolute space (X,Y, and Z) using a GPS base station.

2. *Positioning and analysis of spectral information*. Software to radiometrically correct hyperspectral data is typically included with the IS camera. This software will remove instrument-related noise and convert from "photon counts" to absolute physical radiance units (energy/area/angle). In addition, we need to convert the data to relative units (% reflectance) to be able to compare these data to others collected at different time or with different sensors. This conversion is normally carried out using ground reflectance data collected through the use of spectrally calibrated targets, or using a downwelling irradiance, to compare with the upwelling radiance.

   To orthorectify the data we typically employ a DSM as created through the use of either a LiDAR or a photogrammetric (SfM) point cloud. This will let us position the spectra accurately with respect to other data and surface features. The software to normalize the IS data to reflectance is typically from a third party and may employ relatively complex implementation of Radiative Transfer Models (RTM). However, it has been our experience that as the UAV's are flown quite close to the ground (typically below 50M), the use of RTM is impractical so we employ an irradiance spectrometer to measure the incoming solar irradiance as well as radiometric ground targets. This allows to convert the radiance collected by the IS camera to be converted to at-sensor-reflectance. Further conversion to ground reflectance to accomplished through the use of the radiometric calibration targets. Analysis of the spectra can be carried out using commercial third-party software (for example Harris Geospatial ENVI), open source, or through custom software development using R, Matlab, IDL, or C++, for example.

3. *LiDAR software* is primarily available through third-party vendors such as TERRASOLID software (TerraScan Inc, Finland), or through open source sites such as BCal LiDAR Tools, which allows the user to clean and calibrate the data, classify ground and vegetation points, and produce gridded products. It also will allow the user to create CHM point clouds that can subsequently be gridded. Gridding of the point clouds can be achieved through the use of a number of different third-party software products including ARCGIS and Golden Software's Surfer or Open Source software such as QGIS or GRASS. A large library of LiDAR processing tools is provided by LASTools from Rapidlasso GmbH, Germany. This is a licensed toolbox that has all of the tools necessary to create custom processing streams.

Regulatory Environment

UAV operation in Canada is governed by Transport Canada, through NAV Canada. There are a number of regulations currently (as of Summer 2018) that effect UAV use. These include:

1. All flights are to be carried out within the unaided line of vision of the operator. Depending on the size of the UAV, and surrounding obstructions, this typically restricts us to a radius of no more than 1 km from the operator. This distance is also restricted by obstructions.

2. Unless special permission is obtained the UAV is to be flown within 90 metres above the ground surface.

3. Unless permission is obtained the UAV's are not to be operated within a specified radius from an operational aerodrome (this also includes heliports, and hospitals), float plane operations, and active airfields whether they have local control or not.

4. Operators must have passed a certified ground school and radio operators' examination.

5. All operations are governed by the Special Flight Operators Certificate (SFOC) which are issued by NAV Canada based on a predefined application process.

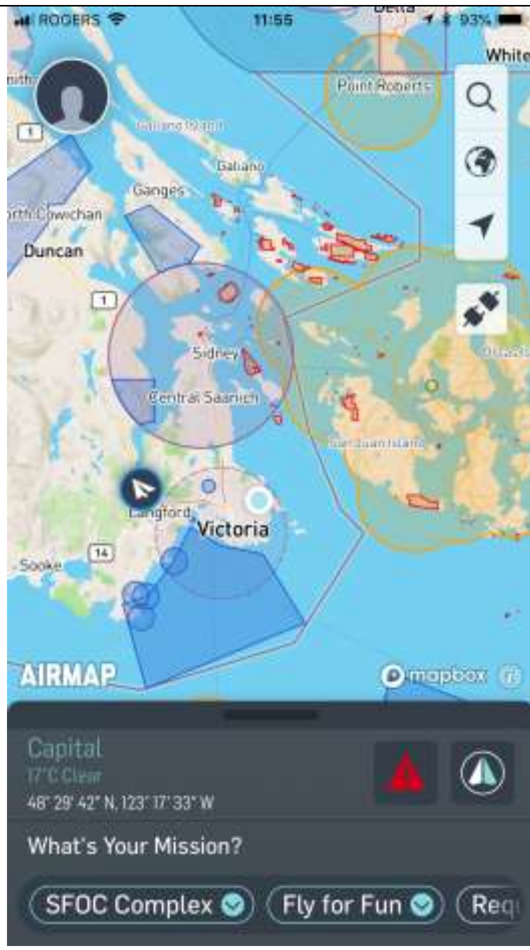

Figure 6 Example of Air traffic control restrictions in the Victoria area.

Fort St John Project

A project was devised to generate data from a UAV platform over industrial sites (gas wells) in northern B.C., north of Fort St. John (see Figure 7, Table 2). We chose a total of 5 well sites to image. These sites were in various stages of deconstruction and reclamation. These sites were also a subset of the sites that were flown previously in 2014, but with a fixed wing platform.

The sites were imaged during the week of September 11-15, 2017[4]. The weather conditions during that week were not ideal (see Table 3), however we did collect a variety of data products over the 5 chosen sites.

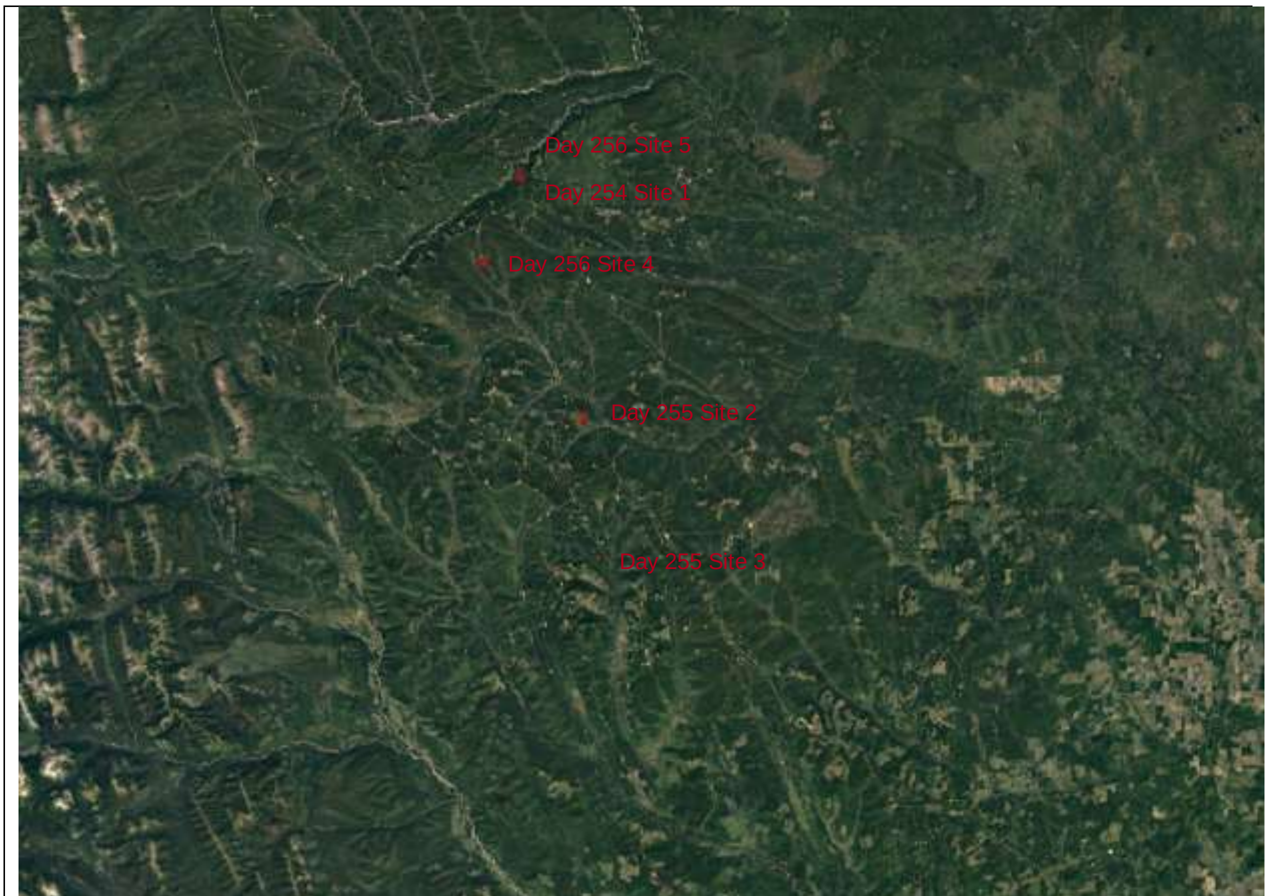

Figure 7. Well site locations chosen for the project.

For this project we flew a DJI Matrice 600 Pro hexacopter. This unit has a payload capacity of ca 6.0 Kg and a typical endurance of 20 minutes. For our payload (see Figure 8) we flew a 12 megapixel RGB camera for orthophotos and SfM point clouds. Also included was the Headwall

[4] The field work was performed later than was originally planned as our deployment to the field was restricted by our (The University of Victoria) having a formal contractual agreement with BCOGRIS.

Name	Date flown	Location-latitude	Location-longitude	Sensors
Site 1	11/10/2017	57 21 02.20N	122 21 03.71E	RBG, LiDAR, IS
Site 2	12/10/2017	57 04 40.53N	122 14 03.37E	RGB
Site 3	12/10/2017	56 55 13.35N	122 12 11.69E	RGB
Site 4	13/10/2017	57 15 15.37N	122 25 12.02E	RGB, LiDAR
Site 5	13/10/2017	57 22 44.80N	122 21 21.90E	RGB

Table 2 Summery of details of sites flown for the survey.

Date/Time	Max Temp (°C)	Min Temp (°C)	Mean Temp (°C)	Heat Deg Days (°C)	Cool Deg Days (°C)	Total Rain (mm)	Total Snow (cm)	Total Precip (mm)	Dir of Max Gust (10s deg)	Spd of Max Gust (km/h)
2017-09-10	17.4	8.7	13.1	4.9	0	0.8	0	0.8	23	61
2017-09-11	19.5	7.4	13.5	4.5	0	3.2	0	3.2	23	76
2017-09-12	14.7	2.9	8.8	9.2	0	1.2	0	1.2	3	41
2017-09-13	14.9	1.8	8.4	9.6	0	0	0	0	32	56
2017-09-14	14.8	4	9.4	8.6	0	0	0	0	24	33
2017-09-15	19.3	1.4	10.4	7.6	0	0	0	0	14	35

Table 3: Meteorological conditions for Fort St John during the week of data collection

Nano Hyperspec IS. We used a 2.5 nm spectral binning (sampling) between approximately 400 and 1000 nm for this project This gives us sufficient spectral detail to yield information on vegetation status. The camera has 640 cross track elements. The LiDAR system flown was a Velodyne VLP 16. This system has 16 separate lasers with a combined 250KHz pulse rate. It has a 360^{o} scan, however, we restrict the area scanned to +/-22.5^{o} from Nadir. This greatly reduces the effective scan rate to between 15 and 16 KHz., however with overlap of flight lines we still obtain between 100 and several thousand points per square metre depending on flighting height.

Figure 8 Configuration of the payload on the M600 and M600 ready to deploy.

The LiDAR DSM point cloud, and that derived from the photography through the SfM processing, are similar in many ways in that they both represent the vertical dimension of the surface. There is a fundamental difference, however, which makes the LiDAR data more attractive. LiDAR is an active sensor which means that it generates its own energy, in the form of a light laser pulse. The fact that it is active means that the pulse can penetrate into shaded areas. Photography, on the other hand, is a passive sensing technology, which means that it relies on external energy sources (e.g. sunlight), so that only surfaces which are illuminated will be measured. The resulting differences in DEM definition is quite noticeable in areas with vegetation cover where for the SfM generated surfaces there may not be any ground points to characterize the ground surface.

For all five sites we attempted to collect the full suite of data from the platform. Unfortunately, we had varied success. We collected photography from all of the 5 sites, and were able to create orthophoto mosaics and SfM point clouds, we had limited success with some of the other sensors. This was, for the most part, due to weather conditions (see Table 1 above) which recorded significant sustained wind speeds, and much higher wind gusts, as measured at the Fort St. John airport. This had a negative effect on the stability of the aircraft during flight. Also, the first two days were overcast with rain which also affected our ability to collect data (ideally, IS cameras should be flown during cloud-free conditions). Finally, the sites chosen were at the end of a long drive from Fort St. John. We chose the sites based on our 2013 larger fixed-wing flight plan, however we did not realize the length of time that it would take to transit to each of the sites. Given the time of year that the survey was undertaken, and coupled with the cloudy conditions, we had less than ideal illumination conditions. We did capture IS and LiDAR data for one of the sites, LiDAR for another but photography for all 5 sites, which have been processed together with the SfM point clouds and orthophotomosaics.

We classified the point clouds and assigned standard class designations to the points (see Figure 9). In our case we differentiated between ground and vegetation so that we could extract the DEM. The points can be classified in more detail however to identify structures, pipelines, etc.

Class	Description
1	Processed Unclassified
2	Ground
3	Low Veg/Strata
4	Medium Veg/Strata
5	High Veg/Strata
6	Buildings (Automated)
7	Noise (High/Low)
9	Water (Hydro Cleaned Areas)
12	Flight Line Overlap
13	Roads
14	Bridges
17	Overlap Default
18	Overlap Ground
25	Overlap Water

Figure 9 LiDAR class designations.

Sites Flown

All five of the sites in Figure 7, above, were flown, but with varying types of data. Site 1 below had LiDAR, photography, and hyperspectral data. This was the only site where the on-site RTK GPS ground station provided us with positional data (see section on data limitations below). Site 4 has both LiDAR and photography, while the other sites only have photography. All of the data collected for this project are included in a separate USB drive.

Included below are samples derived from the data acquired for this project.

Site 1

We collected RGB photography, IS data, and LiDAR for this site. The RGB data were processed using Pix4D SfM software to obtain both the orthophoto mosaic (2.5 cm), and a point cloud. We classified ground points in the LiDAR data and created both DEM and DSM products (to 10cm). We created an NDVI image from the IS data to highlight the vegetated areas within the well site.

Figure 10 RGB Orthophoto mosaic – 2.5 cm resolution

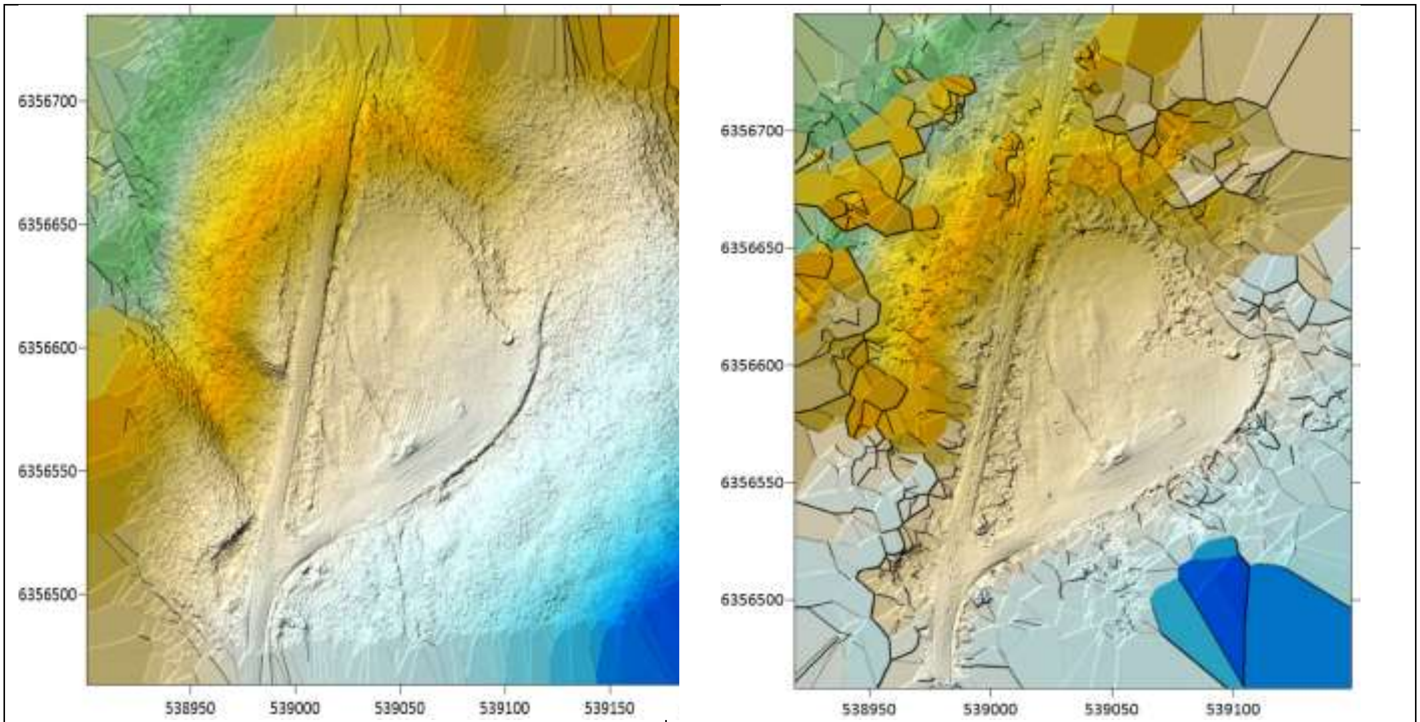

Figure 11 Comparison of the LiDAR derived DEM (left) and SfM sourced DEM (right) both models are gridded to 25 cm.

The two DEM's shown above (Figure 11) provide an insight into the quality of a DEM derived from an active (LiDAR) and passive (photograph-SfM) source. The LiDAR-sourced DEM is less "noisy" than the photo-sourced model. The result is that the LiDAR DEM is smoother and represents smaller irregularities more consistently than the model derived from photos. A second difference is that the LiDAR-derived model, which is an active sensor, is able to penetrate vegetation cover to a greater degree than the photograph. The result is that there is more feature definition in the LiDAR DEM than in the other one. This is immediately apparent in the area to the left of the north-south trending road above, where topographic features are visible in the LiDAR DEM while absent in the DEM derived from the photography.

Figure 12 and 13 represent the IS output (flightlines mosaiced). The nominal spatial resolution for this dataset is approximately 5 cm. Figure 13 provides an output of a relatively simple index (NDVI- normalized difference vegetation index) which yields a measure of foliar biomass. It is also highly affected by soil reflectance so where vegetation is spotty or thin the soil will greatly affect the index values. We had hoped to have the ability to address some of the vegetation health issues, but as the imagery was flown so late in the season senescence masked any opportunity to carry out this analysis. It has been our experience that the window of opportunity for vegetation health data collection is centered on peak green, which occurs relatively early during the summer period. There are other opportunities however to assess changing vegetation state or conditions, but these require multiple acquisitions on anniversary dates.

Figure 12 Hyperspectral (RGB) image – 5 cm resolution

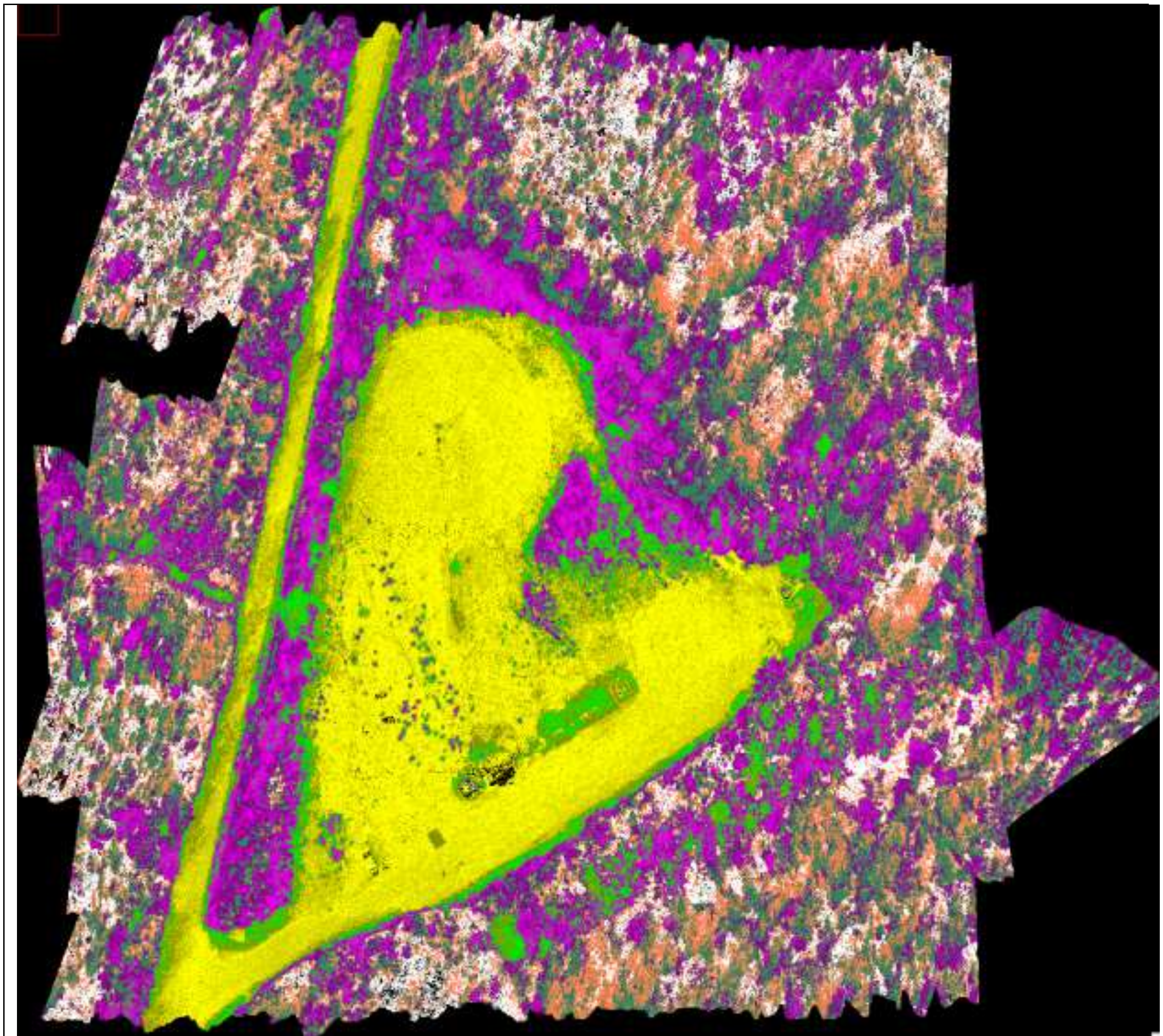

Figure 13 NDVI image derived from the hyperspectral data – **Yellow**: open soil, **Grey**: open vegetation with soil, **Green**: grasses or low shrubs, **Purple**: tall/denser vegetation; **White/Orange**: mostly shadow.

The NDVI image is included in the data delivery, however, it is not georeferenced. We did not include the original raw data in the data delivery.

Site 2

Site 2 data consisted of only photography. We collected RGB photography to approximately 1.5 cm resolution, and derived a photomosaic and SfM point cloud.

Figure 14 Ortho photo mosaic from RGB photography for site 2. Spatial resolution is approximately 2.5 cm.

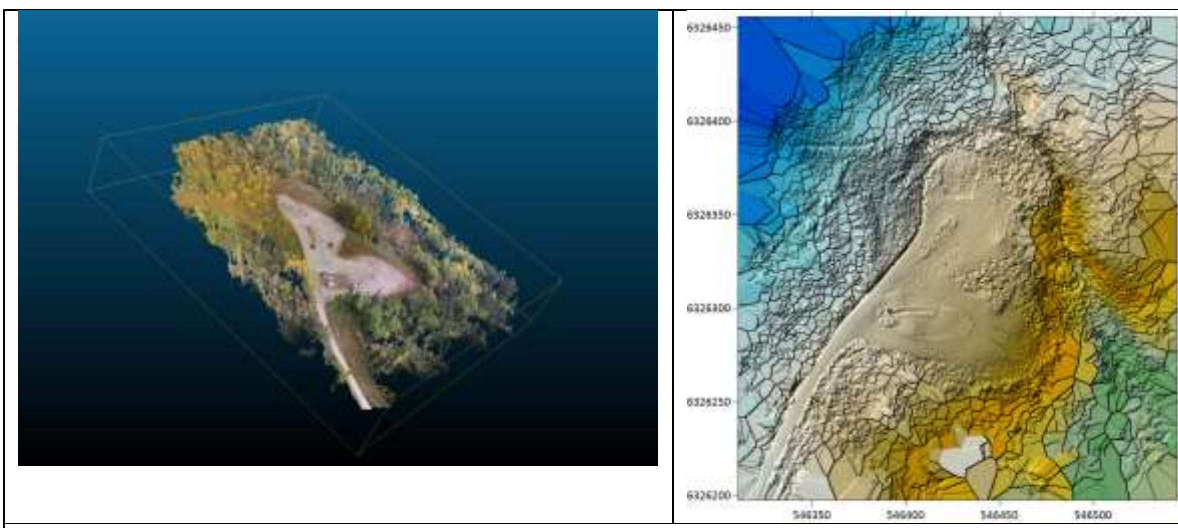

Figure 15. Site 2 SfM point cloud perspective view and a bare earth DEM (gridded to 25 cm) from this point cloud.

Site 3

Figure 15. Site 3 Orthophoto mosaic from RBG photography. Spatial resolution is approximately 2.5 cm.

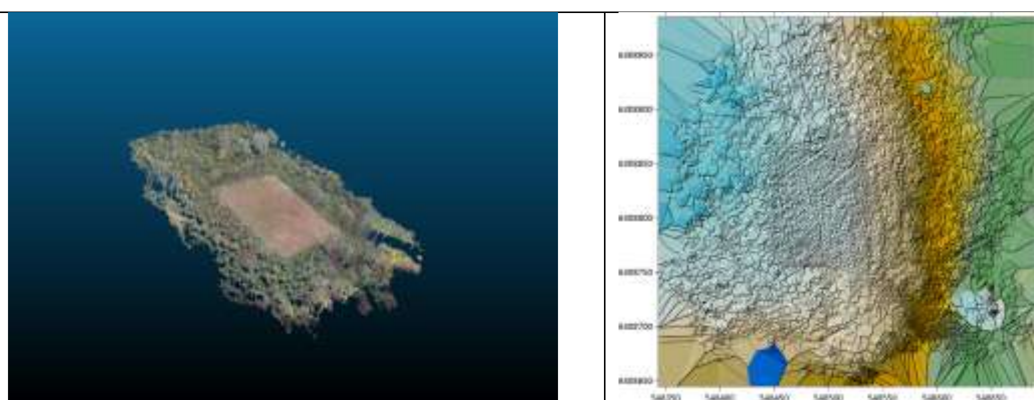

Figure 16. Point cloud perspective for Site 3 and bare earth DEM from the point cloud.

Site 4

Site 4 is covered by both photography and LiDAR. DSM's from both the SfM and LiDAR point clouds have been processed and included in the delivery.

Figure 17. Orthophoto mosaic from RGB photographs. Spatial resolution is approximately 2.5 cm.

Figure 18. SfM Point cloud perspective.

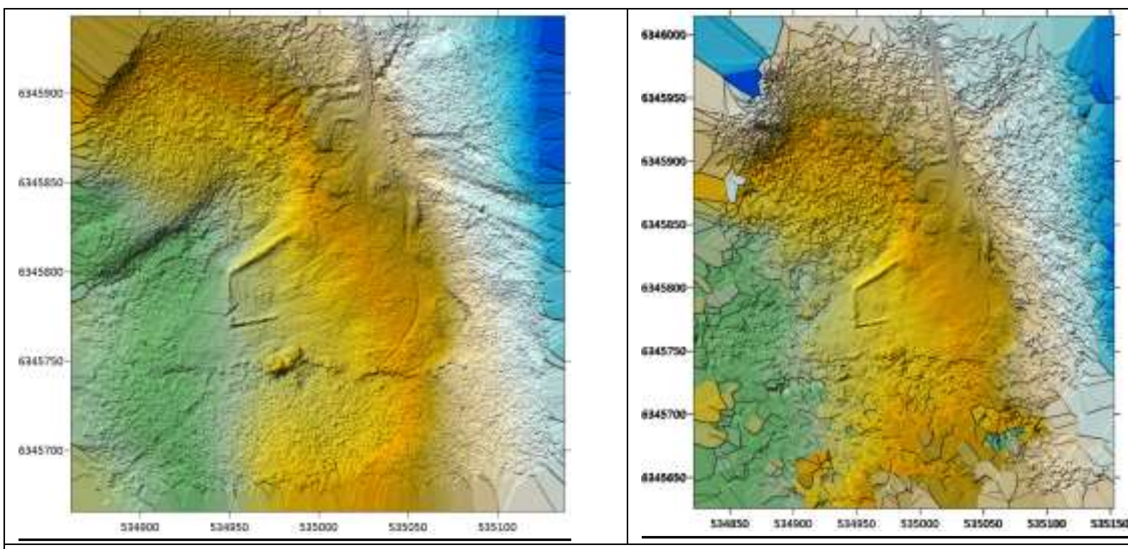

Figure 19. Comparison of the bare earth DEM derived from the LiDAR on left, with SfM point cloud on the right.

Site 5

Site 5 is composed of only RGB photography. A DSM and DEM derived from that dataset have been included in the data delivery.

Figure 20. Orthophoto mosaic from RGB photos. Resolution is approximately 2.5 cm.

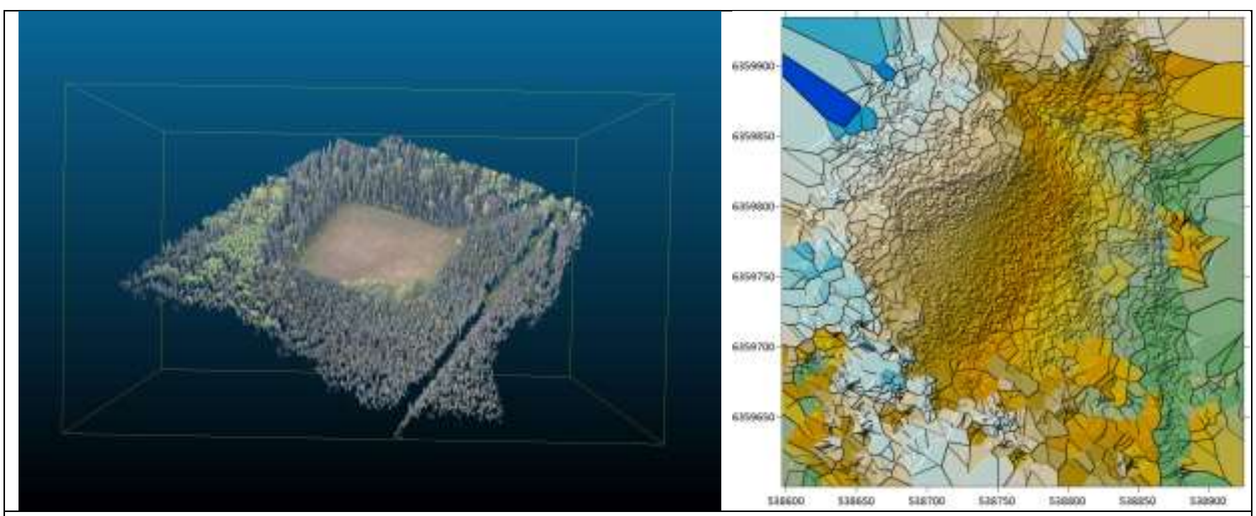

Figure 21. Perspective plot of the SFM point cloud on left and bare earth DEM from the point cloud on the right.

Limitations to the Data

The data collected during this survey was compromised at a variety of levels. Most crucial is that the data collection occurred too late in the season. This has led to a number of issues. The first was the weather. The conditions were less than ideal with strong winds and rain. The second was the low sun angles which resulted in long shadows. The other issue was equipment related. We typically deploy an RTK-GPS base station on site, which allows us to affix accurate real world coordinates to the data collected. This static base station needs to be recording positions for a minimum of 3 hours to resolve positions to the accuracy that we require, and it needs to be operating during the time of the data acquisition so that the data collected by the aircraft can be positioned accurately. We deployed a Trimble R10 RTK GPS to spatially register a control point. The base station was deployed and operated the first day of acquisitions (Site 1 in this report). However, the GPS failed (due to weather conditions) the second day and was non-operational for the remainder of the survey. We did not resort to privately or publicly available GPS data as the baselines associated with those would be too long for UAV surveys[5]. We did however use the positional data that we had for the one site, and so the positioning for that site is accurate (~1cm). In the case of the other sites we do have positional data, however the *absolute* accuracy will not be as high as the data that was corrected using the RTK-GPS base station. In these cases, the positions can be adjusted in a GIS environment using other accurate coverages from other sources. The internal positioning of the data collected was high, so the individual data sets (either RGB photography or LiDAR) was high and yielded spatially coherent coverages. The issue comes when attempting to integrate different coverages from the different sensors.

While we collected viable photographic data, the hyperspectral data collect was subpar for all but one of the sites. This type of data relies on consistent and high-quality solar irradiance (downwelling sunlight). When we have clouds then, unless we have continuous irradiance measurements, it is impossible to address differences between spectra.

Potential Applications

A number of advantages of the data presented through this project and report can be described. The first is that of spatial resolution, while the second is the spatial continuity and permanence of the records. The high spatial resolution of the data collected provides us with an extremely detailed summary of the state of the surface of the site. The high resolution also provides us with the detail necessary to examine the nuances of the site characteristics from topographic irregularities through vegetation changes. The higher spatial resolution also comes with some concern. We normally notice a much higher level of noise in finer resolution data. This is true of both the LiDAR and SfM products. This noise can be mitigated by degrading the pixel resolution to a coarser grid. This will reduce the noise levels so that the signal to noise is

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[5] For standard aerial surveys we could possibly use baselines out to 50 kilometres from the GPS to the survey site. However, for UAV surveys the base station needs to be at the site. The reason for this is that we require very accurate positional data typically within ~1 cm given the high spatial resolution of the data collected.

within respectable ranges. The drawback is that as the grid is coarsened the detailed information is also lost. Alternatively, we can reduce the noise of the grid through the application of a smoothing filter, however there is a threshold between removing noise and removing valid information.

We did not have the conditions necessary to exploit the functionality of the IS data. Typically, we would have acquired the data earlier in the season during peak growing periods. This would have allowed us to gain some meaningful insights into physiological/biochemical abnormalities in the regenerating or introduced vegetation cover. The time delay in getting into the field meant that the vegetation was well into senescence and any analysis would not reveal any biophysical abnormalities or than those attributed to senescence. However, we have found with the UAV-based IS in other applications that we can retrieve very high resolution spectra that are sensitive to relatively subtle changes in the foliar conditions.

Concluding Remarks

The project has demonstrated that relatively small sites can effectively be imaged using UAV's carrying a variety of sensors. The resolutions that can be obtained and the variety of data products can be obtained permit detailed examinations of the state of the well sites. There are constraints, however, that are both technological and environmental in nature. The main environmental constraint is that of weather. These platforms are relatively light, and while the command and control software is able to compensate for many wind/gust conditions, there is an upper limit to the wind velocity that can be accommodated. The most seriously affected data will be the imaging spectrometer and LiDAR, while the RGB photography (which is frame-based), if there is sufficient overlap (≥80% forward and side), can yield high quality imagery. The second environmental condition that is fundamental to the data collected is the quality of the light, primarily the quantity, but also the consistency (i.e. clouds, but in particular scattered clouds are problematic). The main take way from this project in terms of the technology is that it is complex, and to collect high quality (radiometric and spatial) data requires a broad and deep level of expertise. In other words, this is not a *plug and play* technology!

Finally, the primary limiting factor today (2018) is based on regulatory requirements. Given that that the pilot/operator needs to be in visual contact with the platform at all times (that is within a radius of ca 1 km), then it limits the distances that can be surveyed away from the operator. This is coupled with the need to avoid obstructions. It therefore raises the question as to whether the use of UVA's under the current regulatory environment can provide the necessary time saving advantage over the more traditional approaches to the survey for some of these more remote sites.