LESSONS LEARNED: INTEGRATING UAS OPERATIONS INTO AN UNDERGRADUATE GEOSCIENCES PROGRAM

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Abstract

Our department, like many other geo departments, is keenly interested in the potential of Unmanned Aerial Systems (UAS) for collecting data for research purposes. Spatial accuracy is critical for many projects such as those involving mapping and change detection. This accuracy must be repeatable over multiple student projects and multiple flights occurring across hours to years. We have learned a number of lessons over the past two years as we have explored what can be achieved with our reasonably priced UAS, an unmodified Phantom 4 Pro.

Lesson 1: Understand what GPS data are collected by your UAS, what your processing software does with that data to generate the end products that you need, and the limits of spatial accuracy that can be achieved using the UAS alone. Our testing shows that a stock Phantom 4 Pro is capable of repeatable automated flights over the same area with X,Y offsets of 0.5 to 6* m between flights, depending on GPS satellite configuration at flight time. Z values, however, vary dramatically from flight to flight due to the fact that the Phantom 4 Pro calculates initial elevation based on barometric pressure at takeoff. Because barometric pressure varies, this calculation can result in Z value offsets of 10s of meters among multiple datasets of the same area. Data sets align closely in X and Y but are stacked vertically at different elevations.

Lesson 2: Use ground control points (GCPs) to improve spatial accuracy of derived products, and understand the method you use for determining X, Y, and Z coordinates of GCPs. We use 4' X 4' black and white aerial targets evenly distributed across the flight area. We collect coordinates with a Trimble Geo7X receiver with H-Star and correct through Trimble Pathfinder Office software, which queries local CORS stations. Once the imagery is loaded into SfM software, corrected GCP positions are tagged to corresponding target GCPs that appear in multiple images. Although placing GCPs and collecting position data can add 2 hours or more to a mission profile, we have found that decimeter-level accuracy in X, Y, and Z can be achieved, and generated DEMs and orthophotos align well with NYS orthoimagery. It is critical, however, to know whether Z values collected by your device are reported in height above mean sea level or height above the ellipsoid and, if the former, what geoid is being used*.

* blue text is modified from published abstract

RULES:
Because this is
the world we live in

Collecting data for your research is considered a commercial operation and requires an FAA certified Pilot in Command to be operating the UAS or supervising a designated operator.

What does CFR Part 107 entail ?

14 CFR Part 107 certification

Remote pilot Part 107 certification consists of:

- 16 years of age or older
- passing a 60 question multiple choice FAA exam at an authorized testing center, $150.00 test fee
- passing a TSA security background check
- if your have a Part 61 pilot certificate (other than student pilot) and a flight review within the past 24 months, you can apply for Part 107 certification online

- there is not a "flight test" associated with certification

- FAA exam focuses mainly on reading sectional charts, reading aviation weather reports, airspace classification, a bit of flight physics and the Part 107 rules

- multiple study guides are available online both from the FAA and commercial vendors

- Drone Pilot Ground School (www.dronepilotgroundschool.com/) online course was excellent and covered, in great detail, all material needed to pass the exam

Some Part 107 operational rules

- UAV must weigh less than 55 lbs (25 kg)
- maintain visual line of sight (VLOS) of UAV either by Pilot in Command (PIC) or Visual Observer (VO) without binoculars
- UAV may not operate over any persons not directly participating in the operation, who are not under a covered structure, or who are not inside a covered, stationary vehicle
- daylight operations only, 30 minutes before sunrise and 30 minutes after sunset (local time) allowed with anti-collision lighting on UAV
- yield right-of-way to manned aircraft
- maximum ground speed 100 mph (87 knots)
- maximum altitude 400 feet above ground level (AGL)
- can fly up to 400 feet above highest point of structure within 400 feet of the structure, up to floor of Class E air space
- minimum visibility 3 miles from control station
- must fly 500 feet below clouds
- no flights in controlled airspace without FAA waiver
- flight distance from airports depends on airport airspace classification.
- remote Pilot in Command or Visual Observer cannot act for more than one UAV at a time
- operation from moving vehicle only allowed over sparsely populated area

Hamilton College UAS Policy

When Geosciences first acquired our UASs we put in place a policy for UAS operations within the department. Approximately 2 years later Hamilton College, in response to students bringing UASs to campus and the acquisition of UASs by the library for use by the campus community, developed a College wide UAS Policy.

https://www.hamilton.edu/offices/safety/unmanned-aerial-systems-uas-policy

- UAS operators must comply with all federal, state and local rules concerning operation of UAS.
- UAS may only be used on College Property for educational or research purposes.
- UAS used for educational or research purposes must be registered and marked with FAA registration number before being used on College Property.
- Recreational or hobby use of UAS over College Property is prohibited.
- UAS operator must not impose upon another's reasonable expectation of privacy in accordance with the law and social norms.
- Before flying on College Property, the UAS operator must notify Hamilton's Campus Safety and provide a copy of the Remote Pilot Airman Certificate and the FAA's certificate of registration of the UAS.

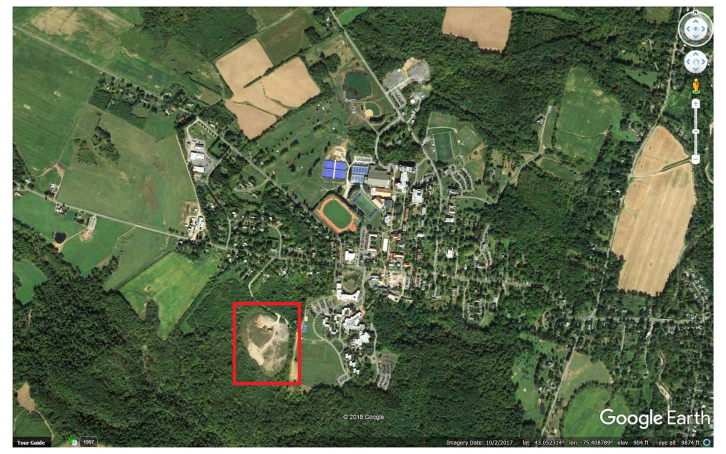
An Unmanned Aerial Systems Permission Form must be filed with Campus Safety prior to operating a UAS on Hamilton College Property or for research/educational use off-campus.

Flight testing area

A construction staging area on the west side of campus is our primary flight testing area.

We chose the site because it is wide open, away from campus activities and because, of ongoing construction on campus, the site is constantly changing, with excavated soil being trucked to the site and bulldozers regularly moving and smoothing the piles.

This is a perfect test site, as parts of the site are changing on an almost daily basis, but there are also fixed objects that are not moving and can be used to compare repeatability of flights over the course of multiple weeks. These fixed objects have been tagged with orange survey paint marks, and positions surveyed with PPK GPS coordinates to use them as ground control points (GCPs) to accurately georeference collected imagery and generated products.



This accessible, yet "remote" from campus activities, site has allowed us to have standing permission from Campus Safety to fly UAS missions at our discretion without having to file permission forms as long as we comply with standing FAA regulations.

A good relation with Campus Safety and an understanding of, and compliance with, flight rules along with our use of high visibility safety vests, hard hats and eye protection on all crew members has allowed for smooth operations on campus and within the local community.

Frame grab from UAS video recorded while testing Active Track settings in DJI Go 4 control app.

Equipment

Hardware
- DJI Phantom 3 standard
- DJI Phantom 4 Pro
  (FAA registered)
- Go Professional Cases custom fitted for each DJI UAS
- Firehouse Technology 4X LED strobe lights
- Hoodman 5 foot folding landing pad
- Icom IC-A14 air band radio
- FLT Geosystems 48" x 48" aerial targets
- MicroAerial safety vests

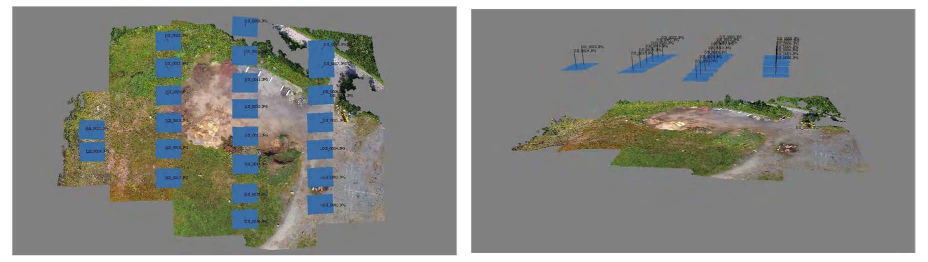
Software
- DJI Go 4 app
- Map Pilot Pro app
- Agisoft PhotoScan Pro ($549 educational pricing)
- Quick Terrain Modeler

Stuff we already had
- Trimble Geo7X GPS
- Trimble Tornado antenna and range pole
- Trimble R1 bluetooth antenna
- Trimble GNSS app
- Trimble Pathfinder Office software
- ArcGIS
- Global Mapper
- PC desktop and laptop computers
- Epson large format printer
- iPad and iPhone
- usual field gear

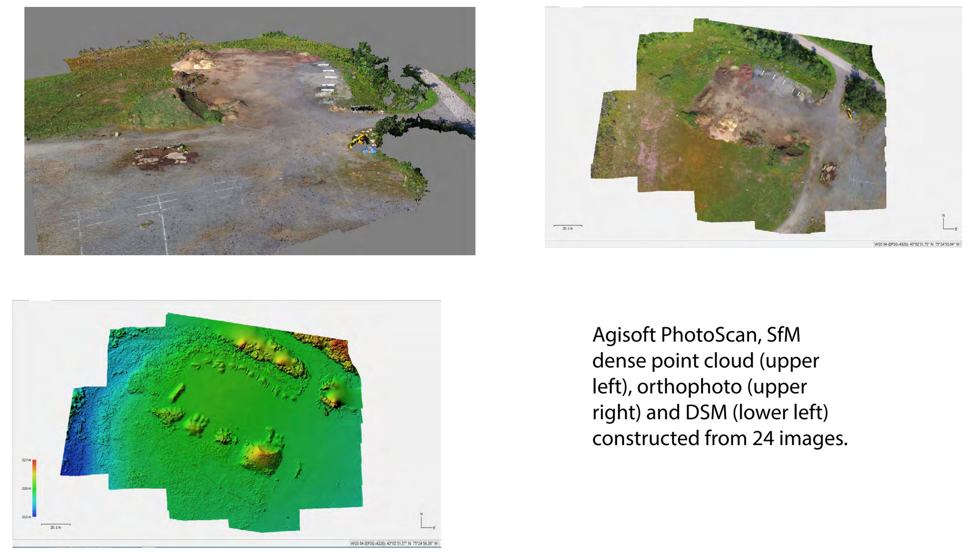
Review: collecting mapping imagery with UAS

We use Map Pilot Pro app to create flight plans to collect aerial imagery for mapping with UAS. Orange dots and yellow lines define boundary of map area. Purple dot indicates launch/landing site. Green dot marks start of mapping flight and red dot marks end of mapping flight. White lines indicate flight

Imagery into Agisoft PhotoScan Structure from Motion (SfM)

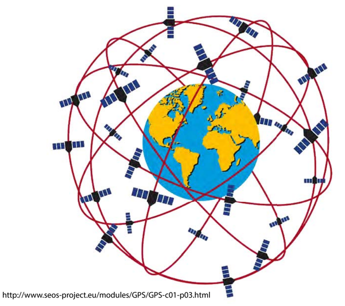


GPS data included in each image EXIF file is used by Agisoft PhotoScan Structure from Motion software (SfM) to roughly position the cameras and then build a sparse cloud consisting of tie-points between overlapping images. Using tie-points and camera positions, the camera positions are "fine tuned" and a dense cloud consisting of millions of corresponding points is constructed.



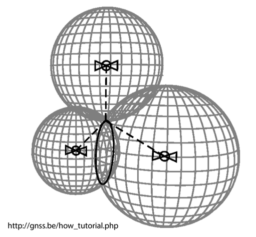
Agisoft PhotoScan, SfM dense point cloud (upper left), orthophoto (upper right) and DSM (lower left) constructed from 24 images.

How Global Navigation Satellite System (GNSS) works



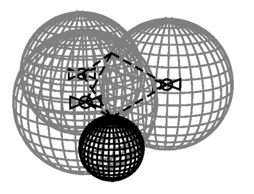
http://www.seos-project.eu/modules/GPS/GPS-c01-p03.html

GNSS consists of multiple satellite constellations, the United States GPS, the Russian GLONASS, the European Union Galileo, the Chinese BeiDou, India's NavIC and Japan's QZSS. Most GPS receivers currently available in the United States only receive signals from either just the United States GPS constellation or both the United States GPS constellation and the Russian GLONASS constellation.



http://gnss.be/how_tutorial.php

- distance from one satellite to receiver defines a sphere around the satellite
- distance from receiver to second satellite defines a circle of intersection between the two spheres
- third satellite sphere defines 2 points on the circle, one of which is the receiver location
- a fourth satellite sphere defines the correct point that is the receiver location



http://gnss.be/how_tutorial.php

- with receiver on the Earth's surface, Earth blocks satellites below user's horizon
- receiver only sees satellites in the sky above the receiver
- ideally three satellites define two points of intersection with one point close to the Earth's surface and the other above the Earth' surface
- mathematically the Earth's surface acts as the fourth sphere

In general, the four spheres will not intersect at a single point due to atmospheric interference, bounced signals from nearby buildings and/or poor satellite geometry. To overcome this issue, the distance to as many satellites as possible is measured, and a least square fitting is calculated to determine the most likely position of the receiver based on the propagation times from all observed satellites. (http://gnss.be/how_tutorial.php)

The receiver's calculated position is the X, Y, Z position of the receiver relative to the WGS84 spheroid/ellipsoid. The Z position is the Height above Ellipsoid (HAE) and is recognized as having errors of between -100 m and +70 m with respect to the geoid (altitude above mean sea level AMSL), depending where you are on the planet.

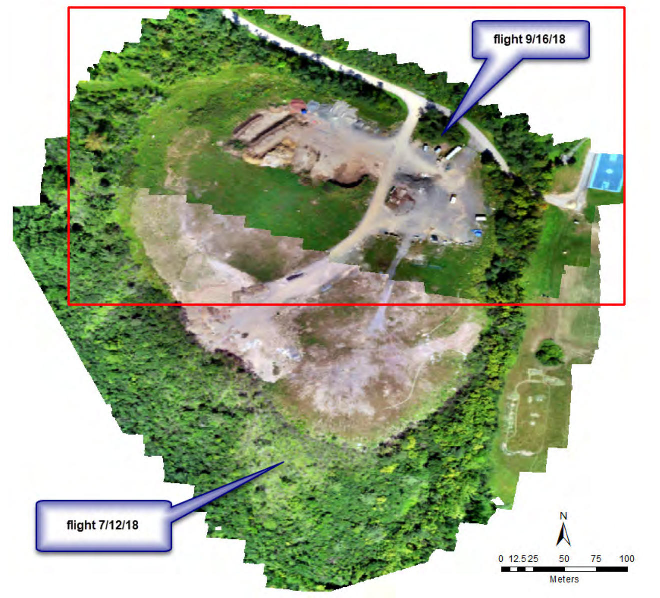
Structure from Motion (SfM) processing with Agisoft PhotoScan Pro

Processing UAS collected imagery with Agisoft PhotoScan is a straight forward, menu driven set of steps to go from a collection of individual images to a 3D point cloud, digital surface model (DSM), and an orthoimage. Because almost all of the calculations to derive these products occurs with little to no user input it is difficult to know exactly how the data is being processed.

It appears that depending on the size of the area and/or the number of images processed, the software will generate results have different spatial alignment. These data were also processed across a couple of different versions of the software as it is updated on a fairly regular basis.

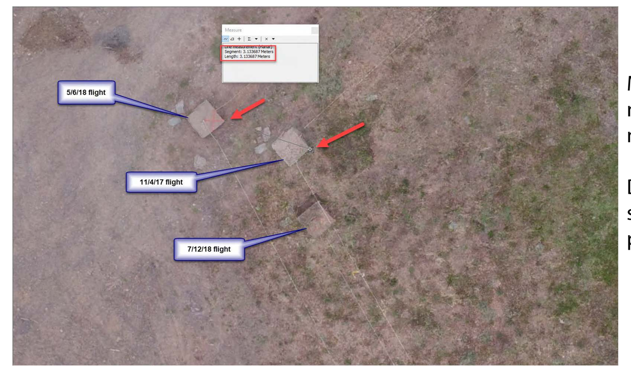
Flights over approximately the same area, a year apart, show pretty good spatial alignment of orthophotos viewed in ArcMap. Processed orthophotos created from imagery using only the UAS collected GPS coordinates associated with the imagery and no ground control point (GCP) data, viewed in GCS WGS84.

Increasing the transparency of the upper layer (9/23/17) the offset between the two processed orthophotos can be seen and measured. These two datasets consist of 150 and 250 images respectively. Getting a "good fit" model for a small number of photos over a relatively small area seems to result in not too much distortion in the processing of the two different data sets.



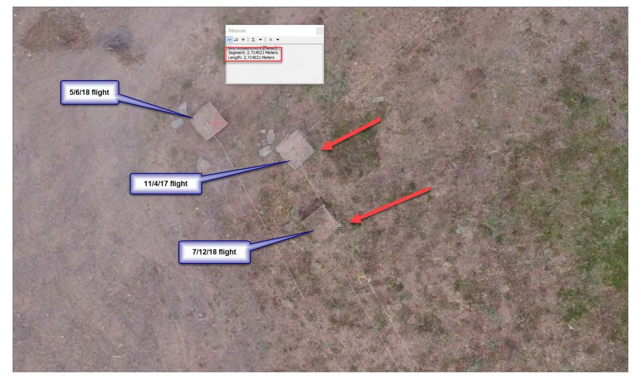
Combining generated orthophotos of a small area with that of a much larger area in ArcMap still shows reasonable spatial alignment between the two datasets. The larger area was built from 522 individual UAS photos. Again, imagery constructed using only the UAS GPS data associated with the imagery, no GCP data, viewed in GCS WGS84.

Increasing the transparency of the upper layer (9/16/18) the offset between the two processed orthophotos can be seen and measured. These two datasets consist of 250 and 522 images respectively. Getting a "good fit" model for the large area dataset required more distortion of the model than that used for the smaller area dataset. Resulting in a larger offset of fixed features between the two datasets.

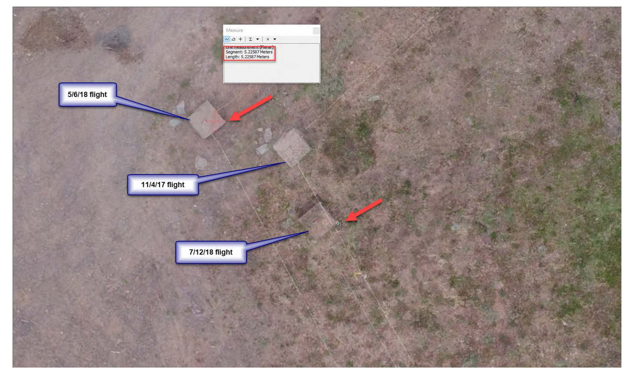


Multiple autonomous flights of the same area do not guarantee the SfM software will build the same model each time.

Data from three autonomous flights using the same flight plan, results in three slightly differently processed orthophotos.



No GCP data used when processing these data, only the GPS data associated with the UAS imagery.



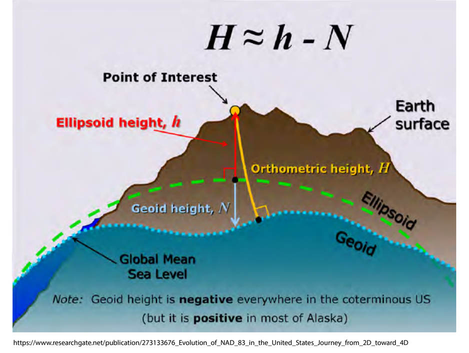
Differences in time of day, vegetation and other features in the scene probably resulted in slightly different tie points and camera calibration values, resulting in slightly different dense point cloud models which carried over into the generation of DSM and orthophoto. Data also spans multiple versions of the software.

GPS elevation and UAS elevation data

Previous section examined X, Y position data associated with UAS collected imagery and the resulting products produced by SfM software. Now we need to look at the Z position data associated with UAS imagery and how UAS elevation and flying height is determined.

- GPS elevation data accuracy is poor and only survey grade GPS units and RTK or PPK processing of data results in reliable/accurate Z values.

- GPS elevation data is a calculation based on the location & height of the GPS receiver relative to an ellipsoid, commonly the WGS84 ellipsoid, and the corresponding location of the receiver on a geoid.



https://www.researchgate.net/publication/273133676_Evolution_of_NAD_83_in_the_United_States_Journey_from_2D_toward_4D

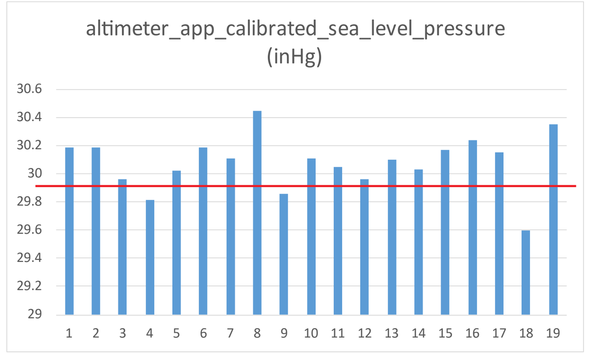
The HAE value is the height of the GPS receiver above the ellipsoid (WGS84 assumed) at the calculated X, Y position of the receiver. The elevation of the GPS receiver (AMSL) or orthometric height, is a calculation of the ellipsoid height minus the geoid height. In order for a GPS unit to display elevation, it must reference a geoid stored in the unit. The accuracy of the X, Y position, to derive a HAE, and the quality of the geoid used in the calculation will impact the accuracy of the elevation value.

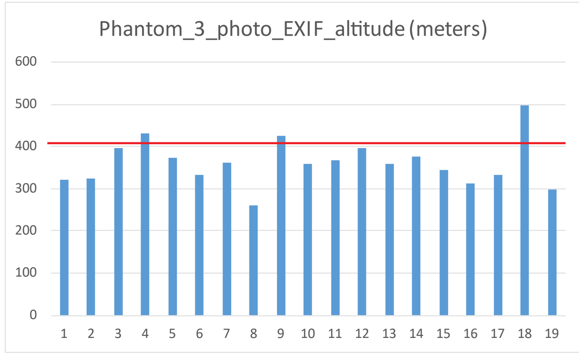
From the USGS website on GPS (https://water.usgs.gov/osw/gps/)

... it must be noted that all GNSS derived elevations, though proven through time to be fairly accurate, are only modeled results. Orthometric heights (or elevation) are simply calculated as the ellipsoid height minus the geoid height (both modeled values based on location).

Barometric pressure is substituted for GPS to calculate Z for UAS elevation/altitude data. Prior to takeoff the UAS measures the barometric pressure at the takeoff location and using standard sea level pressure (29.92 inHg) calculates the altitude of the takeoff point. This value is then set to zero and flight altitude is calculated by the change in pressure between the pressure measured at takeoff and the pressure at a given flying height. The flight app displays this difference as altitude in meters or feet.

Although more accurate, and consistent over the short flying time of a given UAS mission, there is a repeatability problem with this system. Because the barometric pressure at the time of takeoff is used to calculate the elevation of the takeoff point, that same point may be assigned very different elevations at different times due to changes in the atmospheric barometric pressure.





On random dates between mid-September and mid-October barometric pressure was measured at a fixed point and, with the UAS sitting on the ground, a photo was taken at the same time. Barometric pressure and the elevation data tagged to the UAS photo were plotted. Red lines show standard sea-level pressure (29.92 inHg) on the graph of barometric pressures and surveyed elevation of the location (404 meters AMSL). Notice that when the measured barometric pressure was higher than standard sea-level pressure the corresponding takeoff elevation was lower than measured and when barometric pressure was lower, the corresponding takeoff elevation was higher. Also note the variation of takeoff elevation from a low of 259 meters to a high of 498 meters for exactly the same location.

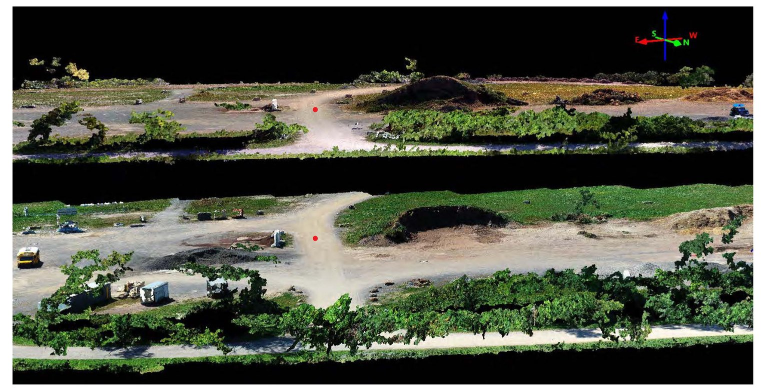
A decrease of 1 inch of Hg is equal to a change of 1000 feet in elevation. So a change of 0.1 inHg is equal to a 100 foot change in elevation (roughly 30.5 meters). Line 4 on the barometric chart is 29.96 inHg and is associated with an elevation of 424.695 meters. Line 10 on the barometric chart has a value of 29.86 inHg and is associated with an elevation of 395.17 meters.

29.96 inHg - 29.86 inHg = 0.1 inHg   424.695 meters - 395.17 meters = 29.525 meters

The measured barometric pressure is associated with an elevation of zero at takeoff and changes in barometric pressure are used to calculate the flying height above ground level (AGL). Because the takeoff barometric pressure is associated with zero elevation at takeoff, changing barometric pressure as the UAS ascends accurately reflects the flying height (AGL) even though the calculated elevation of the takeoff point might be wildly different from the takeoff point's actual elevation. This is why multiple autonomous flights from the same takeoff point over the course of days, weeks or months, may show varying takeoff elevations in the image EXIF data, but the flying height is consistent between flights.

Varying takeoff elevations are the issue

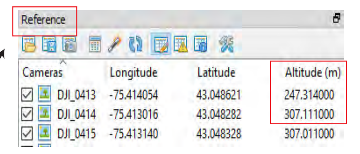
Although datasets collected of the same area over the course of days, weeks or months have reasonable alignment X,Y, the varying calculated takeoff elevations generate differing Z values for the processed dataset products.



LAS files generated from dense cloud data viewed in Quick Terrain Modeler (QTM) for the same area flown about a year apart.

X, Y alignment looks pretty good, but Z is poor. Neither dataset was processed with GCP data so elevation positions are based on the elevations associated with the UAS imagery from each flight. Red point on upper surface has an elevation of 229 meters, red point on lower surface has an elevation of 201 meters, an almost 30 meter vertical offset between datasets.

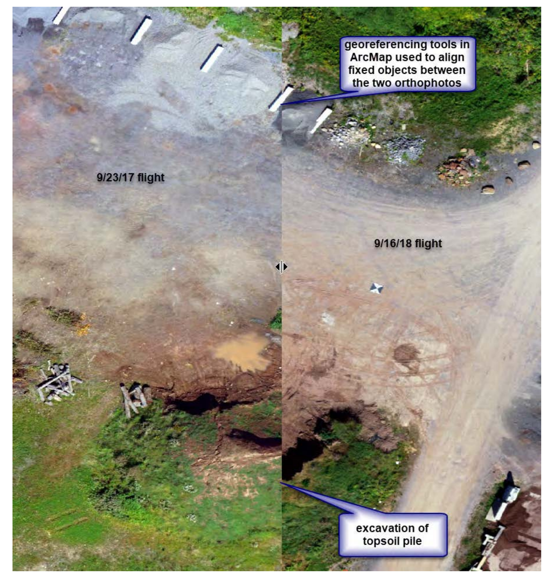
just in from Agisoft support team, *"DJI is writing two altitude values to the image meta data (XMP header of the image) - AbsoluteAltitude that seems to be a barometric height and RelativeAltitude that is the height above the take off point. To the image EXIF the AbsoluteAltitude value is written. So it seems that this height is incorrect - PhotoScan just reads EXIF and populates the corresponding cells in the Reference pane without any additional transformation of the coordinates."*



Reference

Cameras	Longitude	Latitude	Altitude (m)
DJI_0413	-75.414054	43.048621	247.314000
DJI_0414	-75.413016	43.048282	307.111000
DJI_0415	-75.413140	43.048328	307.011000

Calculated takeoff and in flight elevations for a flight 60 m AGL. Actual measured takeoff elevation 292 meters.



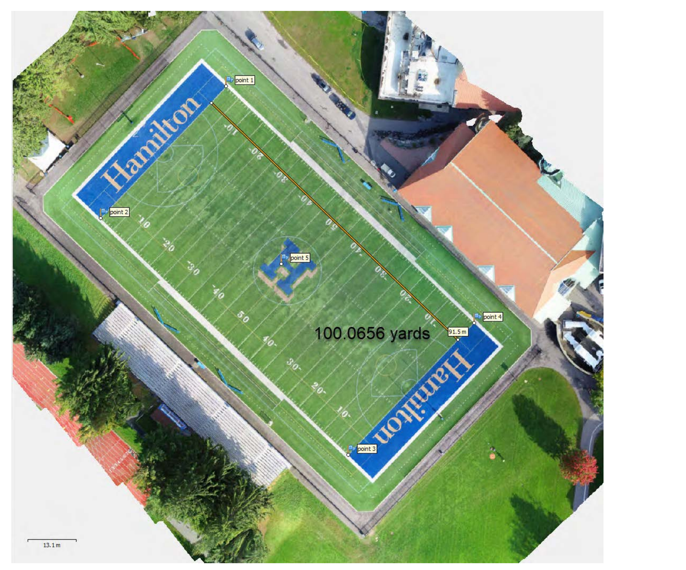
Identifiable fixed objects can be used to georeference different datasets for X, Y alignment.

Ground control for both X, Y and Z correction of modeled data

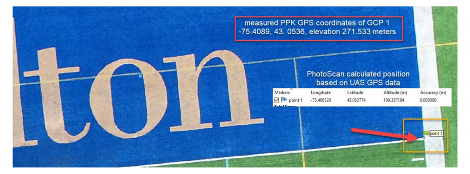
Ground control points with surveyed values are the only way to spatially correct generated SfM products. Some UAS have integrated RTK GPS that will produce accurate GPS data that SfM software can use, although Z values still tend to have some issues. These systems tend to be on expensive ($10,000 +) systems or are costly add-ons to existing technology. DJI just announced the Phantom 4 RTK mapping UAS which will be a huge step in generating spatially accurate data, although the listed price for the UAS and support base station is in the $8,000 dollar range.

For now, placement of GCPs and measuring their location is the method I use on all flights needing spatially accurate alignment.

A GCP can be something that is easily recognized in the imagery, a painted mark, or a commercially available aerial target.



Football field makes a great reference test with its defined shape and markings. Orthophoto created from 42 images collected from UAS flying 60 meters AGL. Image on left is orthophoto created without using GCP values. Note that the field is slightly longer than it should be. Image on right is orthophoto created using GCP points at the 4 corners of the field. Notice the field length is now accurate. The point at the center of the "H" (point 5) is used as a check point.



PhotoScan estimated location of GCP 1. Note X, Y position is close, Z is dramatically off from actual measured GPS coordinates of the GCP .

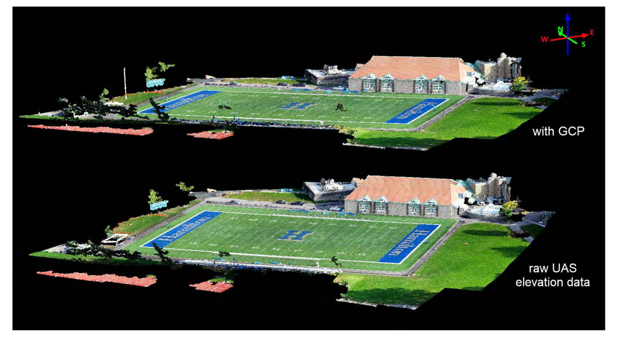


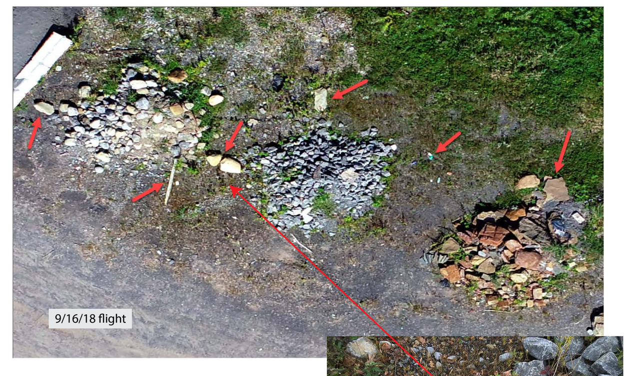
Image above shows a 3D view of the point clouds of the two processed datasets in Quick Terrain Modeler. The lower surface is located based on the elevation calculated by the UAS at takeoff. The upper surface is located at the correct elevation based on the surveyed values of the GCPs.

Elevation at the "check point" near the cross bar of the "H" is 199.796 meters on the lower surface and 271.535 meters on the upper surface. A difference of 71.739 meters.

Surveyed elevation for the "check-point" is 271.638 meters, a difference of 0.103 meters between the model surface and the "real-world" surface. The Geo7X with H-Star and PPK correction has a specified accuracy of 0.1 meter.

To update campus imagery for our Facilities Management group, UAS imagery was collected of the new baseball and softball field complex and added to a base image from the 2017 NYS Orthoimagery Program. NYS flies updated imagery of our area every 5 years so even before the imagery is accessible on the web it is out of date for many features. Multiple GCPs were used to attain good spatial accuracy.

Visual change detection does not necessarily need GCP data



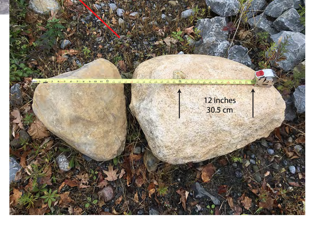


Image at far left is screen shot in ArcMap showing two datasets of approximately the same area that were flown about a year apart. Using the large concrete dividers and a couple of other fixed items visible in both images, alignment was achieved that allowed comparison of rock piles and how they have changed over the course of a year. Clearly the resolution of the UAS imagery is high enough to easily resolve objects 25 cm and even smaller.

This kind of visual change detection does not require precise spatial accuracy and can be easily accomplished simply with the location data collected by the UAS during flight, without the need for GCPs or precise surveying of GCP positions.