

COMPARISON OF THE PRACTICAL APPLICATIONS AND LIMITATIONS
OF INSAR AND STRUCTURE FROM MOTION DEPICTIONS OF SURFACE
ELEVATION FLUX FOR ACADEMIC PURPOSES

By

John Andrew Scherer

Department of Geography, University of Colorado at Boulder

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Thesis Advisor:

Dr. William Travis, Department of Geography

Defense Committee:

Dr. Michael Dwyer, Department of Geography

Dr. Paul Weimer, Department of Geological Sciences

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ABSTRACT

This paper seeks to identify the strengths and weaknesses of two remote sensing methods used for determining surface elevation flux (the difference in land surface elevation heights over a given time period): Interferometric Synthetic Aperture Radar (InSAR) and Drone Imagery processed using Structure from Motion (SFM) Techniques. This goal was accomplished by processing imagery from both platforms separately, before conducting a study of the same area and comparing the two methods analytically. A time-series of interferograms was generated on the study area of the Climax Mine and Mill near Leadville, CO and multiple drone flights were flown over an additional study area near the towns of Lyons and Loveland, CO over an active flagstone quarry. InSAR was also processed over the latter study site for the comparison between the two systems. The pros and cons of the two methods are discussed and displayed in Table 1. InSAR measurements favor vertical accuracy at the expense of spatial resolution and SFM images favor high spatial and temporal resolution at the expense of efficient data collection over large study areas. This research is important to the field as it will help scientists and researchers better understand and differentiate between which remote sensing platforms are the most appropriate for a given research topic. The research in this study also laid the ground work for the creation of a model or software toolbox which may serve to integrate the strengths of both platforms into research in future academic endeavors.

INTRODUCTION

INTRODUCTION TO THE FIELD OF REMOTE SENSING

When conducting research on environmental and geological phenomenon which involve some change of elevation or displacement observable on the surface of the Earth, scientists often seek to quantify and spatially analyze these events. Available methods are normally divided into two categories: in-situ observations and remote sensing. In-situ observations are those which are observed either by an investigator in-person, or by some instrument or device that is in direct contact with the feature being observed. On the other hand, remote sensing is defined by the National Oceanic and Atmospheric Association (NOAA) as, “the science of obtaining information about objects or areas from a distance, typically from aircraft or satellites.” (NOAA, 2018). This paper will only consider the applications of remote sensing as it relates to academic research and will not deal with in-situ based observations.

INTRODUCTION TO InSAR AS A REMOTE SENSING SYSTEM

There are many applications of remote sensing to academic research, but this paper investigated two specific methods of remote sensing which are used in determining both the general topography (or 3-D shape) of an object or area as well as the change throughout time of this topography (or surface elevation flux). The first method investigated is one of the now most commonly used instruments in imaging the earth’s surface called Interferometric Synthetic Aperture Radar (InSAR) which is a satellite-based system capable of measuring surface changes to the centimeter-scale. The system has seen expansive use since the early 1990’s and is becoming

ever more popular as data has dramatically decreased in price from nearly \$8000 per image (Airbus, 2014), to being free of cost on certain platforms such as the European Space Agency's (ESA) Copernicus Open Access Hub (Pritchard, 2006).

In the simplest explanation, InSAR platforms are active-sensing systems meaning they provide their own energy source, in this case microwave radiation, so there is no need for an external source (such as the Sun as there would be in a passive-sensing system). This

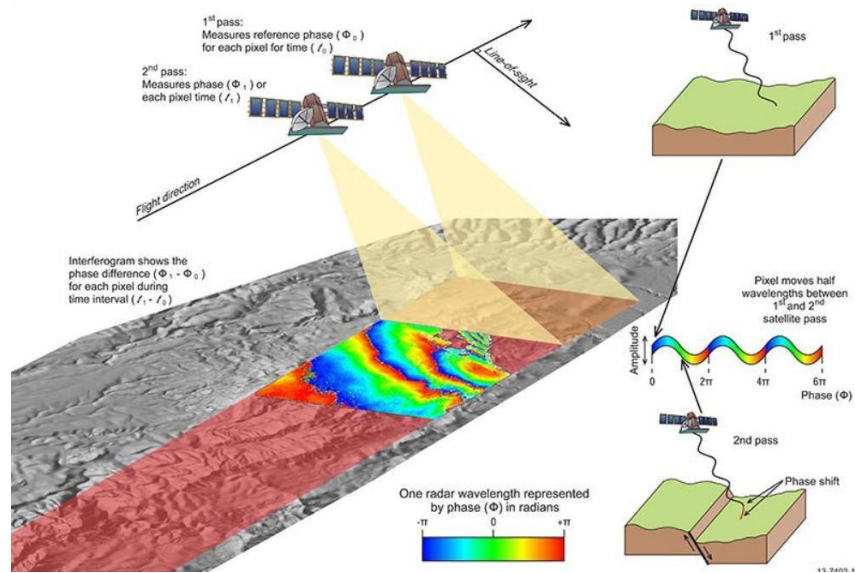


Figure 1: Image depiction of how InSAR system works. In the top of the image the demonstration of the two passes of InSAR satellites are shown. On the right side the phase difference detection is shown. And the scale at the bottom depicts the color palette for the period of an InSAR wavelength. (Geoscience Australia, 2019)

means InSAR satellites may operate day or night, and in all weather conditions to provide continuous satellite coverage of the earth with as close as a 6-day period between images of the same geographic area being possible. By knowing the time between the outgoing and incoming pulses of the radar beam, InSAR platforms can estimate the distance between the satellite and the ground surface, through a process known as radar altimetry. InSAR platforms are unique however in the fact that they can detect the exact point along the phase of a microwave that the beam leaves and returns at giving an additional degree of accuracy to the system. When two of images of the same area are gathered, software analysis can difference the two images to create an image of the difference in phase of each pixel between the collection dates, this image is known as an interferogram. Analysis of an interferogram, or time-series of multiple interferograms can yield

valuable information about how the surface of the object or area has deformed or has been changing throughout time. (ESA, 2019).

INTRODUCTION TO THE USE OF DRONES TO CREATE SFM-GENERATED DEMs

One of the next most popular methods of generating maps of surface topography and analyzing surface elevation flux is the use of stereophotogrammetry or structure from motion (SfM) photogrammetry, which use standard optical camera sensors to gather information from topography usually from an aerial platform, either a large aircraft or a smaller unmanned aerial vehicle (UAV) or drone. Described by Humboldt State University:

Structure from Motion (SfM) is a technique which utilizes a series 2-dimensional images to reconstruct the 3-dimensional structure of a scene or object. SfM can produce point cloud based 3-D models similar to LiDAR. This technique can be used to create high resolution digital surface models (including digital elevation models) and models of objects with consumer grade digital cameras. The relatively new technique has been made possible by advances in computers, digital cameras, and unmanned aerial systems (UAS). Together, these advances have now made it feasible for a wide range of users to be able to generate 3-D models without extensive expertise or expensive equipment. (HSU, 2019).

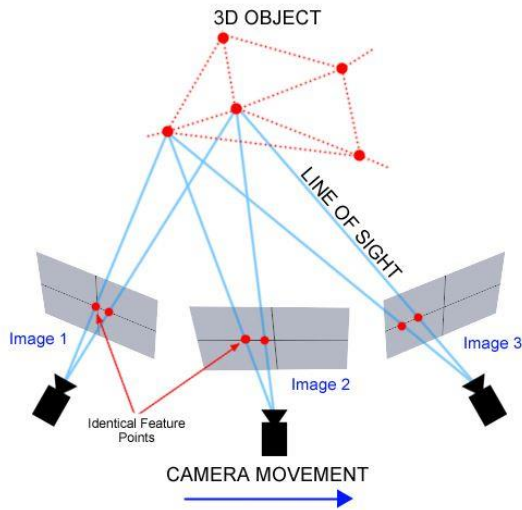


Figure 2: This image depicts the general idea behind the feature tracking associated with structure by motion. The feature points are identified by the red dots and the cameras show how different orientations of sensors allows the creation of a three-dimensional model. (Mason, 2019)

As explained from the Humboldt State University description SFM (or SfM, colloquially) has the ability to generate high resolution maps of surface topography through the utilization of much more affordable and accessible equipment and software. Specialized software for SFM operates on the principle of feature tracking, which identifies features prevalent through multiple images in the collection from a drone or aircraft (HSU, 2019).

The orientation of the camera sensor is also

included in the metadata which allows the software to generate a “cloud” of points with x,y, and z coordinates where the x and y-coordinates correspond to the spatial position on the ground, such as latitude and longitude or Universal Transverse Mercator (UTM) coordinate grids, but additionally hold vertical elevation estimates in the z-coordinates of the point cloud. This information can then be imported into a variety of remote sensing software packages such as ENVI (Harris Geospatial) or ArcGIS (ESRI) to process the information into a map of the surface topography, called a Digital Elevation Model (DEM). When two separate DEMs of the same area are collected, they may be subtracted (differenced) from each other and the surface elevation flux can be determined. Similar to as what was discussed in the section: Introduction to InSAR as a Remote Sensing System, a time-series of DEMs can be generated to show change over time.

This paper investigated the differences between the two methods in terms of resolution (spatial and temporal) as well as the advantages and limitations each system and a further analysis into how these factors play into the selection of an appropriate sensor for academic research. It is

my hypothesis that InSAR images will be better suited for imaging expansive and inaccessible areas or for when vertical accuracy is needed for the research objectives. On the other hand a scientist would want to choose SFM if the features needed to be identified are smaller than the large pixel size of the InSAR system or when a high temporal resolution is needed.

METHODS

This study aimed to quantify and describe the differences between InSAR and SFM primarily through the experimentation and use of both systems in a project. When conducting real-world use of the remote sensing methods the first step was to go through the process of creating several InSAR interferograms with 12-day periods. The study area chosen for this site was the Climax Mine and Mill, a large Molybdenum mine near Leadville, CO since surface elevation flux is likely detectable due to the ongoing mining operations at the plant. The second was to create two DEMs using SFM and drones. The study area for this was different than the Climax mine as we determined the presence of snow through the winter months around the mine would hinder collection of accurate measurements. Instead, a flagstone quarry near the towns of Lyons and Loveland, CO were chosen because the lower elevation and warmer temperatures of the area mean that consistent snowpack is not present and thus images could be collected for most of the year. Lastly, InSAR radar images were collected of the Lyons site at times around when the drone flights were conducted in order to compare the use of drones and InSAR using the same study area.

InSAR INTERFEROGRAM GENERATION

For InSAR interferogram generation the images were collected from the Copernicus Open Access Hub web interface which allows access of various remotely sensed products from the ESA

for free download for educational and personal use. The satellite which collected the images was the Sentinel-1A satellite launched by the ESA on April 3, 2014. The Sentinel-1 system carries a C-band synthetic aperture radar (SAR) which operates at 5.405 GHz in frequency (wavelength is approx. 5.45 cm). The satellite operates in four modes: Strip map Mode (SM), Interferometric Wide Swath Mode (IW), Extra Wide Swath Mode (EW), and Wave Mode (WM). The products used in this analysis were in the IW mode which has a resolution of 5x20 meters. The satellite is in a near-polar, sun-synchronous orbit with a 12 day repeat cycle and 175 orbits per cycle for a single satellite. Data from the satellite is transmitted to the Copernicus program within one hour of ingestion and is available in four types of data products: Raw Level 0 data, Level 1 Single Look Complex (SLC), Level 1 Ground Range Detected (GRD), and Level 2 Ocean (OCN) data. The only data product used for this research was the SLC data which includes images with both phase and amplitude information, with some pre-processing data done by the ESA. (ESA, 2019).

The software used to process the InSAR data was the Sentinel Application Platform (SNAP) which was developed by the ESA specifically for processing images from Sentinel-1 and other Sentinel Program satellites. SNAP was used because all the necessary toolboxes and extensions are already built-in. Other software used for the generation and evaluation of InSAR interferograms included ESRI ArcGIS to display the final GeoTIFF images spatially, SNAPHU (Statistical-cost, Network-flow Algorithm for Phase Unwrapping) which was developed as a means of two-dimensional phase unwrapping by Chen and Zebker at Stanford University, as well as Google Earth Pro to display the interferograms on a familiar and easy to use interface.

The process of creating an interferogram follows some variation of these basic steps:

- a. **Image Collection:** A set of images are downloaded from a web-based interface for accessing InSAR data such as the Copernicus Open Access Hub. Extra attention is

made to the satellite track at which the images are collected (as the tracks need to be the exact same) and the dates at which the images are collected (more time between images usually results in less coherence, or similarities between pixels in the images). These files are around 4.5 GB compressed and >7.0 GB uncompressed so the image download, and extraction process is both time and memory intensive.

- b. **Orbit File Application:** The next step is to apply the orbit file to each image which contains the precise information about the 3-D orientation of the satellite in orbit as well as pitch, roll, and yaw information about the orientation of the sensor which helps calibrate minor differences in platform and sensor orientation between the two collection dates. (ESA, 2019).
- c. **Back Geocoding:** Back geocoding is a process of georeferencing both images relative to each other. Back geocoding, or reverse geocoding converts pixel numbers into coordinates and identifies ground reference points shared between the two images to closely fit the two images together in a spatial sense. This step is important because terrain influences the backscatter of SAR images and a correction is needed. The images are referenced to a DEM, most commonly the Shuttle Radar Topography Mission Global DEM (SRTM GDEM), which has a resolution of between 1- and 3-arc seconds (30x30 and 90x90 meters, respectively). (ESA, 2019).
- d. **Split and Deburst:** The image is first split by swath (vertical columns) and then burst (horizontal rows) to only contain the study area desired for analysis, which greatly speeds up computing time for each additional step. Next the image is debursted which is the removal of no data and/or overlapping data from the bursts of the satellite, this also helps to speed up processing time and increase data accuracy. (ESA, 2019).

- e. **Interferogram Formation:** Next the software generates an interferogram of the two images using the differencing method which subtracts the phase differences between the two images. The bands outputted in this step are the Intensity, Coherence and Phase. The intensity band shows the raw radar backscatter of the combined two images, the coherence shows how similar the two images are, and the phase shows the difference in phase between the two images which is the foundation for further analysis. (ESA, 2019).
- f. **Goldstein Phase Filtering:** The next step commonly done in interferogram formation is to filter the generated interferogram. Phase Filtering, specifically using the algorithm generated by Goldstein & Werner (1998) helps to reduce decorrelation and phase noise that is in the image as a result of thermal noise, temporal change, and baseline geometry. Upon applying the Goldstein phase filtering the resulting image often has a reduced phase noise. This improves both the overall accuracy in measurement of the image as well as makes other post-processing effects such as phase unwrapping more efficient.
- g. **Phase Unwrapping:** “While an interferogram’s fringes show topography or deformation, the height change between fringes is ambiguous. The phase is only known within 2π . Phase Unwrapping resolves the uncertainty and allows displacement values to be derived from the product.” (UAF, 2019). Phase unwrapping is done in SNAP by exporting the wrapped and filtered phase image to the format specified by the external SNAPHU program. The file is run through any available C++-based console on the computer and an unwrapped phase output file is generated. This output file is then

imported back into SNAP with the original wrapped phase image as a reference and the unwrapped phase is generated in SNAP (Chen & Zebker, 2002).

SFM DEM GENERATION

In order to generate an image from SFM photogrammetry a process, similar to that shown in the InSAR Image Generation section of this paper, must be followed. While SFM can be generated



Figure 3: DJI Phantom 4 Drone used in imaging the April 1, 2019 flight of the Lyons study site.

from a variety of platforms the most common is through the use of UAVs or drones. These aerial vehicles are affordable, easy to transport, use and have a wide support network of manufacturers and dealers across the globe. Three models of drones were used in this research, all from DJI, one of the most popular drone manufacturers for both professional and hobby-use drones in the world. The models used for this research were the DJI Phantom 4, the DJI Mavic Pro, and the DJI

Mavic Air. All have remarkably similar camera and navigation specifications so differences in the image collection between the platforms are very minimal, which is an advantage of using drone platforms as one can be easily substituted for a different make or model in the field, something not easily done when working with satellite data.

Steps in generating an SFM image (DEM) from a drone:

1. **Flight Path Generation:** The first step is to generate the flight path of the study area, this is important because due to the battery life of drones (usually ~30 minutes) only a limited area can be imaged and while multiple areas can be mosaicked together, smart flight planning is critical for the resolution and the accuracy of the measurements. Besides the area the altitude is another consideration which must be taken into effect. The higher the altitude the greater the Instantaneous Field of View (IFOV) which makes it easier to gather a large areal extent of data however the spatial resolution is reduced, also there is the additional time which the drone must use to ascend and descend from the higher altitudes which can affect the areal extent via battery life.
2. **Image Collection:** Once the flight path is generated, it is usually uploaded to the drones built in software on a phone, tablet or computer, this flight path converts the graphical extent, altitude, and desired resolution into a series of x, y,z coordinates which the drone will follow over the flight. This information is downloaded directly to the drone which is then launched, images the study area and returns to the original starting point or a specified landing point. The images from the drone are then uploaded from the drone to a computer, usually by way of a removable SD card or flash memory system.
3. **Point Cloud Generation:** While there are numerous ways to manually generate SFM images, most users utilize some sort of software-based system that use complex algorithms and sometimes Artificial Intelligence (AI) to compute the SFM point clouds. The software used for this study is DroneDeploy which is a subscription-based software running through the cloud. Data is uploaded from the user's computer to the cloud and the software automatically generates and exports a series of products to the user, one of which being a

point cloud in the .LAS format which is the same as which is used for Light Detection and Ranging (LiDAR) images allowing manipulation in a variety of software suites.

4. **DEM Generation:** This point cloud is then downloaded and opened in a software designed for LiDAR manipulation and analysis. We used ENVI LiDAR 5.5 which is based off the popular remote sensing platform, ENVI, which is developed by Harris Geospatial. The point cloud is turned into a DEM and is then available for export to any number of platforms for geospatial analysis.

RESULTS

As seen in the previous Methods section there are both similarities and differences in the implementation and analysis of both InSAR and SFM system. Below are figures showing the various levels of images generated with both systems.

InSAR INTERFEROGRAMS

STUDY AREA



Figure 4; Shows the Climax Mine and Mill Study area near Leadville, CO (located to the southwest). The road in the image (depicted by the yellow polyline) is Colorado Hwy 91. Imagery Captured by Google Earth and Digital Globe. North is Up. The bounding coordinates of the study area are: NW (39.723695, -106.227755), NE (39.421172, -106.125463), SE (39.359621, -106.123279), and SW (39.358561, -106.227104).

InSAR GENERATED DEM

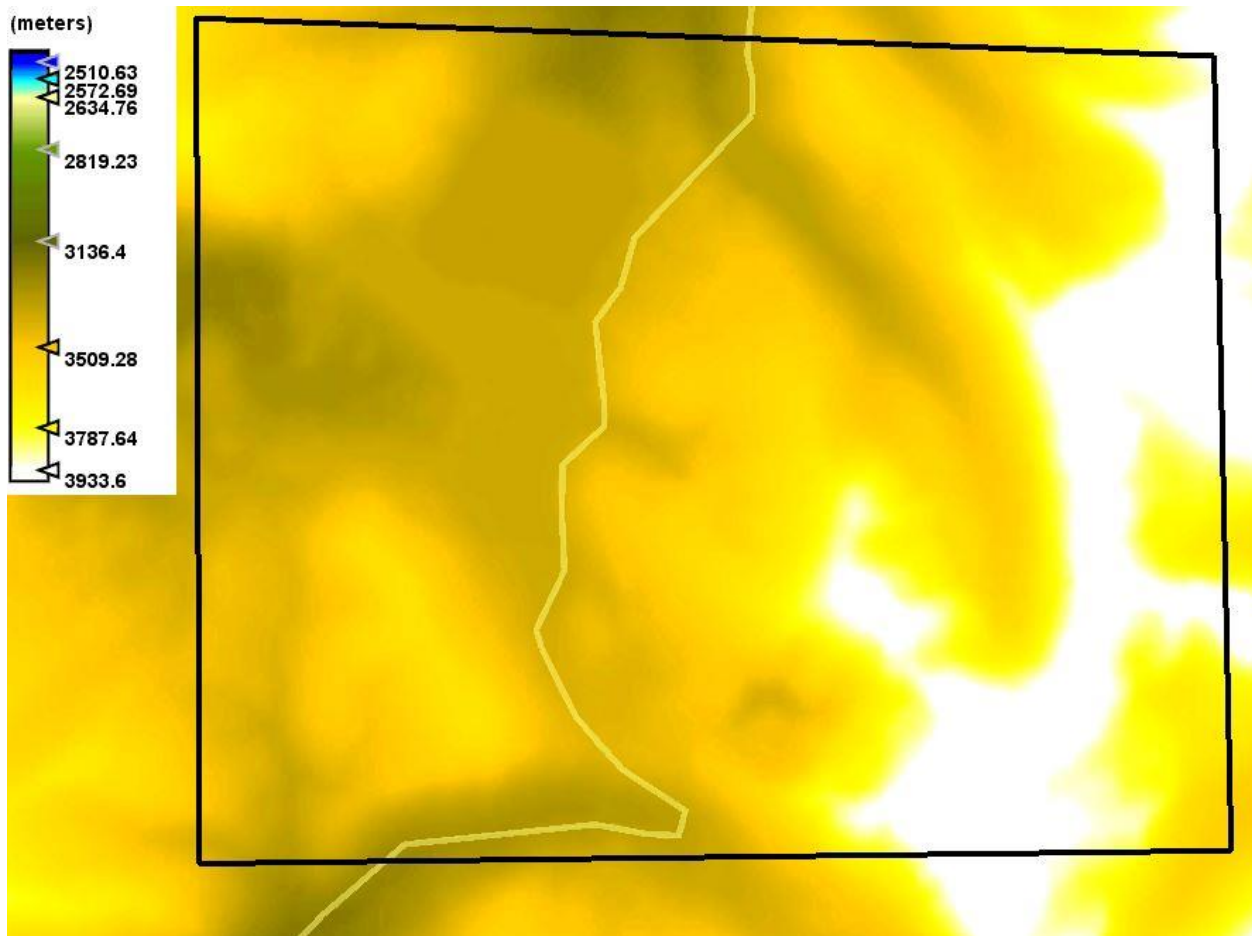


Figure 5: Shows a Digital Elevation Model (DEM) generated from InSAR imagery over the Climax Mine and Mill Study area. Areas of high elevation are depicted in Yellow and White tones, while areas of low elevation are identified by blue, green, and brown tones. The yellow polyline running through the study area is Colorado Hwy-91. North is Up.

InSAR PHASE MEASUREMENTS

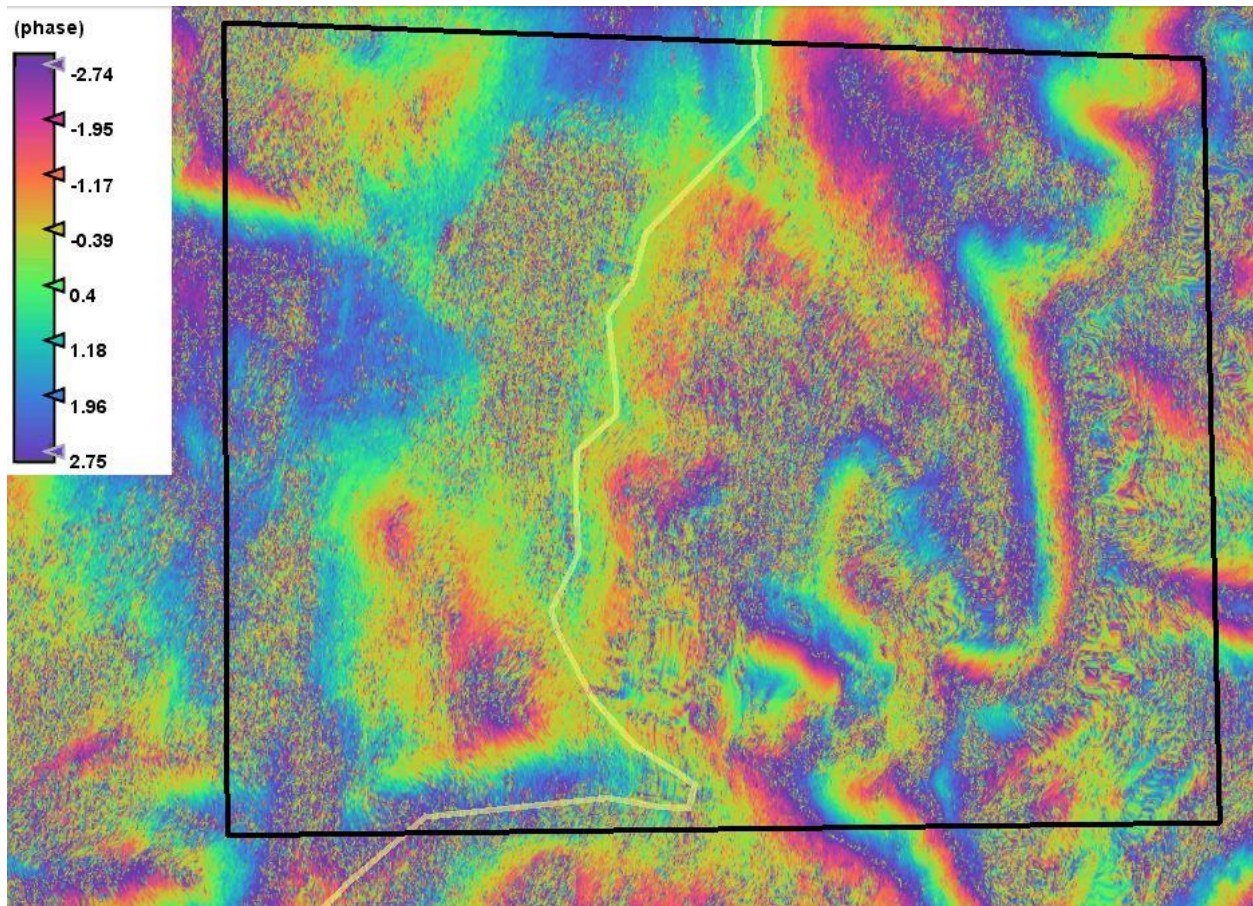


Figure 6: InSAR Interferogram showing raw phase over the Climax Mine and Mill Study Area. The fringes in the image show surface deformation but are arbitrary and displacement cannot be measured directly from this image. Images taken by the European Space Agency's (ESA) Sentinel-1A platform on the dates of May 21st and Jun 2nd, 2018. Data accessed from the ESA's Copernicus Open Access Hub. Scale is in radians, 2π radians is ~ 5.45 cm of deformation.

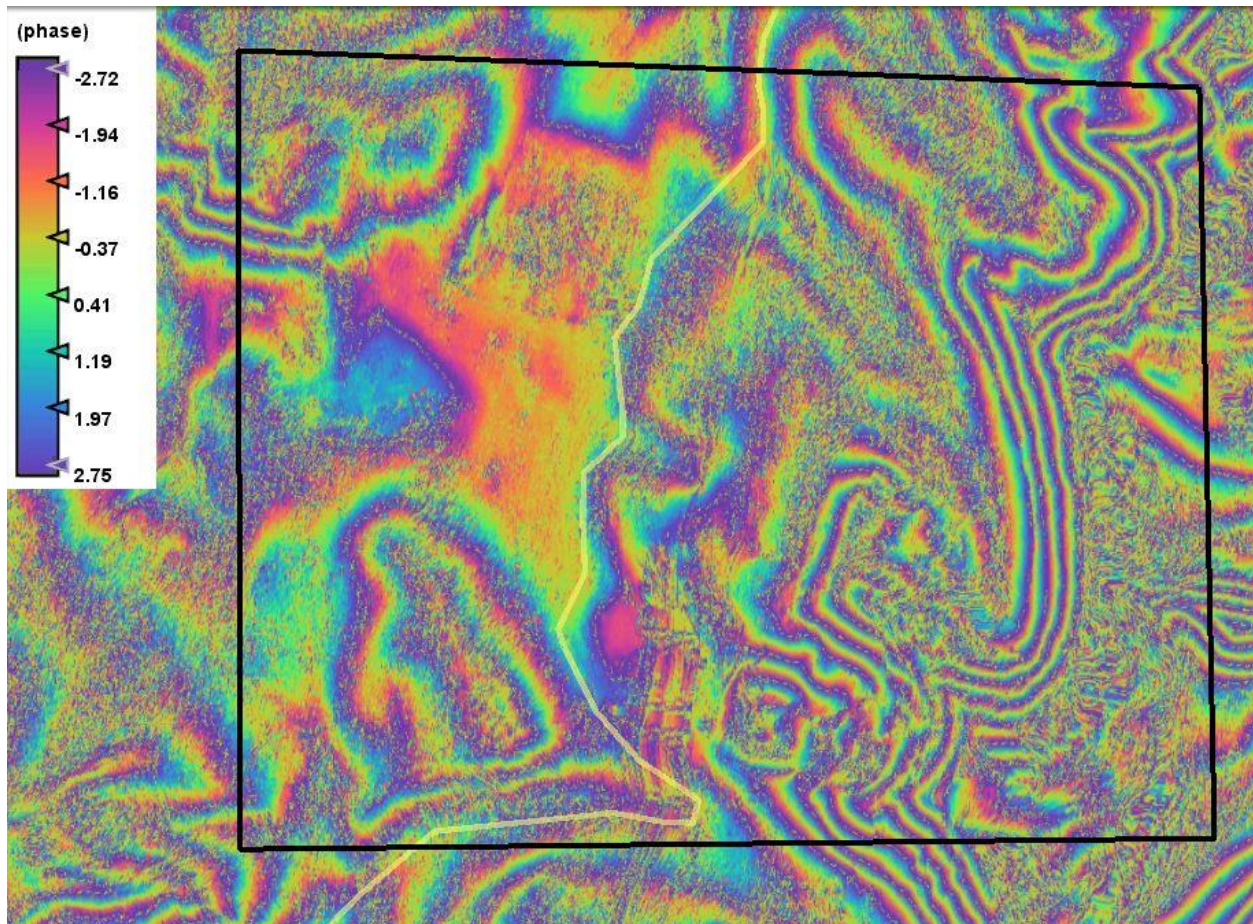


Figure 7: Interferogram showing raw phase over the Climax Mine and Mill Study Area. The fringes in the image show surface deformation but are arbitrary and displacement cannot be measured directly from this image. Images taken by the European Space Agency's (ESA) Sentinel-1A platform on the dates of June 2nd and Jun 14th, 2018. Data accessed from the ESA's Copernicus Open Access Hub. Scale is in radians, 2π radians is ~ 5.45 cm of deformation.

InSAR UNWRAPPED PHASE MEASUREMENTS

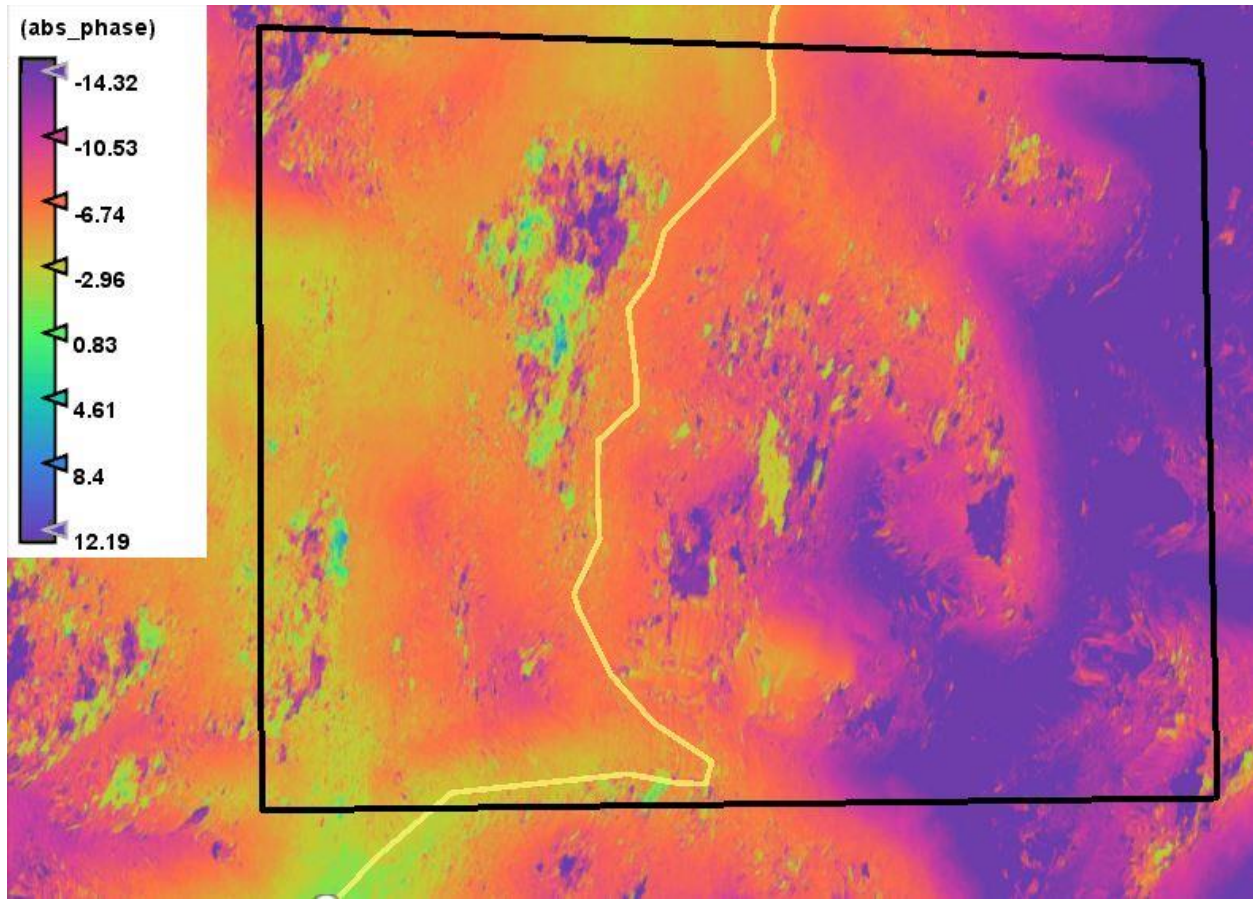


Figure 8: Unwrapped Phase version of Figure 6 which shows the absolute phase change over the Climax Mine and Mill study site. Scale is in radians, 2π radians is ~ 5.45 cm of displacement.

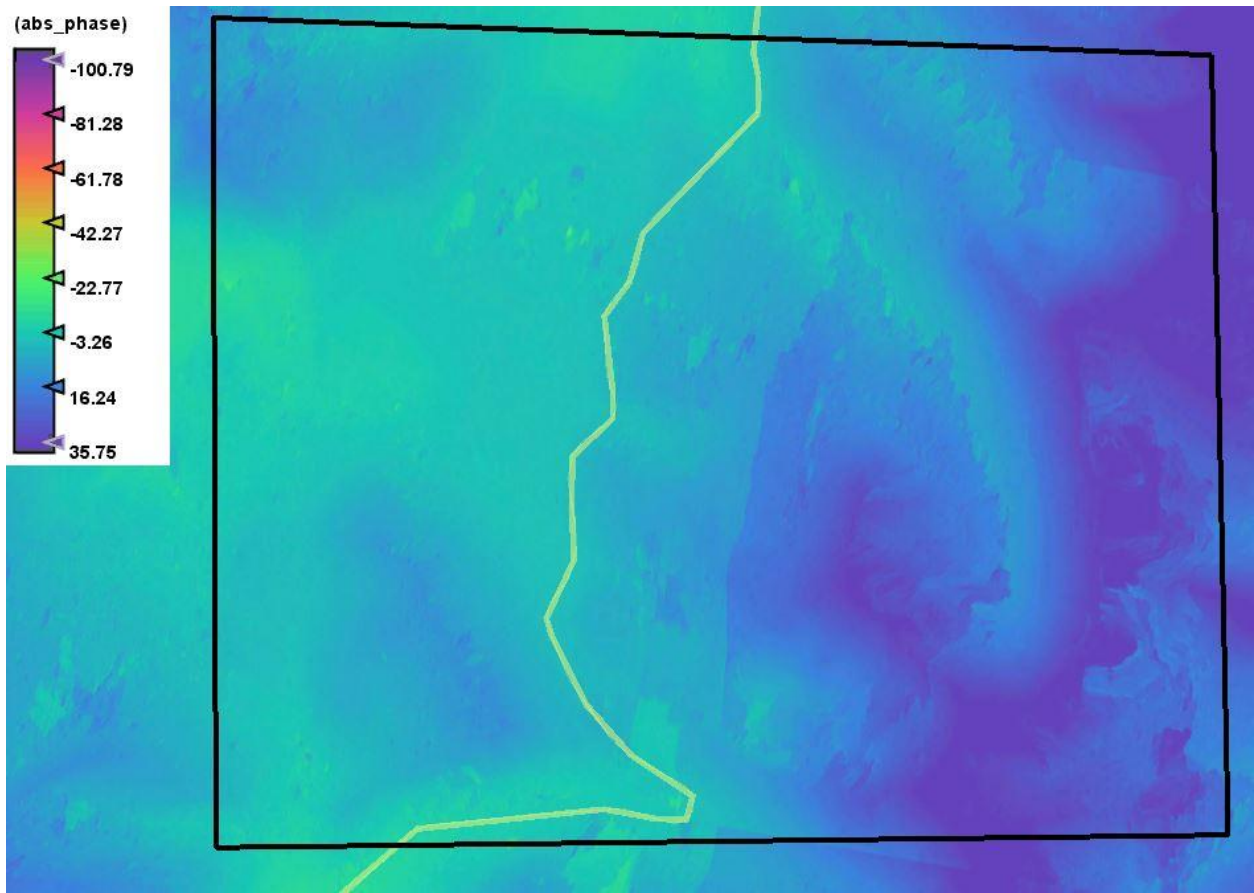


Figure 9: Unwrapped Phase version of Figure 7 which shows the absolute phase change over the Climax Mine and Mill study site. Scale is in radians, 2π radians is ~ 5.45 cm of displacement.

SFM-GENERATED DEMs

ORTHOMOSAICS

Orthomosaics are the raw optical images taken by the drones. They represent a series of many images that are mosaicked together to create a final composite image. These represent those taken from the Lyons field site on November 10, 2018 and April 1, 2019.



Figure 10: Orthomosaic of the drone imagery collected over the Lyons study site. This image was taken at an altitude of 400 ft above ground level (AGL) using a DJI Mavic Pro drone and 12 MP sensor. Imagery taken on November 10, 2018.



Figure 11: Orthomosaic of the drone imagery collected over the Lyons study site. This image was taken at an altitude of 400 ft above ground level (AGL) using a DJI Phantom 4 drone and 12 MP sensor. Imagery taken on April 1, 2019.



Figure 12: Maximum zoom focus area of the Lyons study site. This image shows the relative size of features which the drone and software are able to recognize. Image was taken on November 10, 2018.



Figure 13: Maximum zoom focus area of the Lyons study site. This image shows the relative size of features which the drone and software are able to recognize. Image was taken on April 1, 2019.

POINT CLOUDS

Point clouds represent the first product created by SFM photogrammetry. Each point represents the x, y, z coordinates that are generated by the SFM software. Point clouds are the first step in creating DEMs.

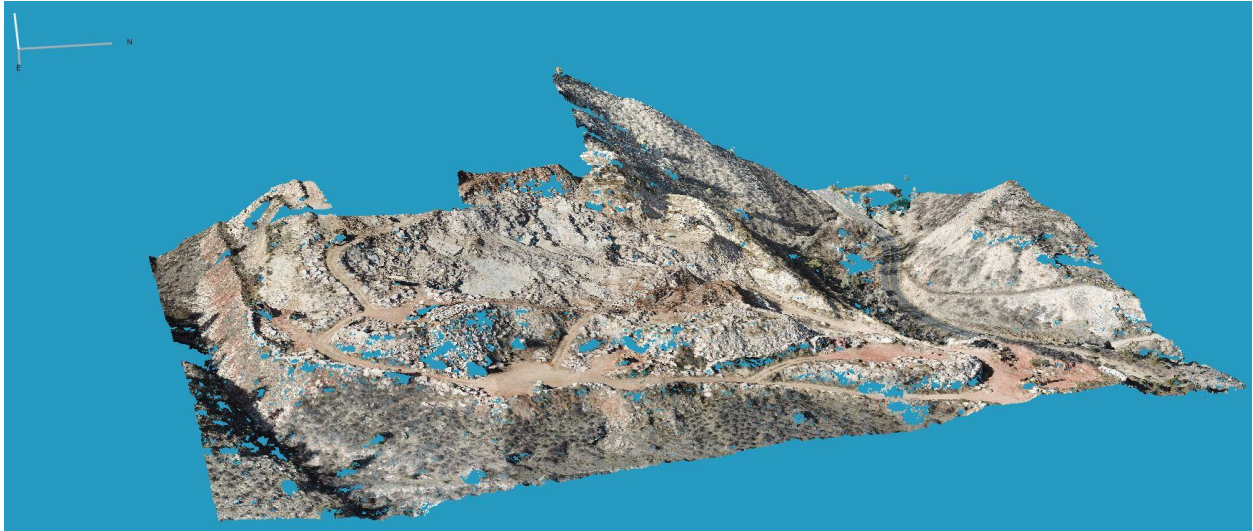


Figure 14: Point cloud generated of the Lyons study site taken on November 10, 2018. Each pixel against the blue background represents a single data point in the point cloud. Data points are colored in the same hue as the associated ground pixel on the orthomosaic (Figure 6) for easy reference between the two- and three-dimensional depictions of the study area.

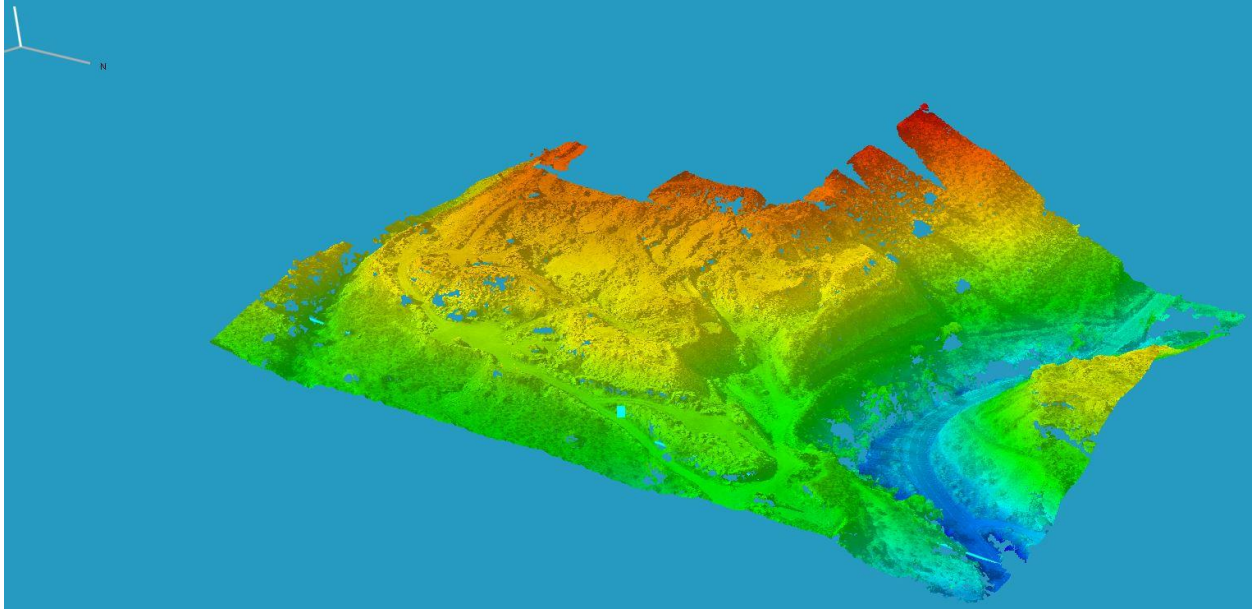


Figure 15: Same point cloud as shown in Figure 14. This example is shaded to show relative height. The highest points are depicted in Red and of 1670 meters above mean sea level. The lowest point in the image is 1604 meters above mean sea level and is depicted in blue.

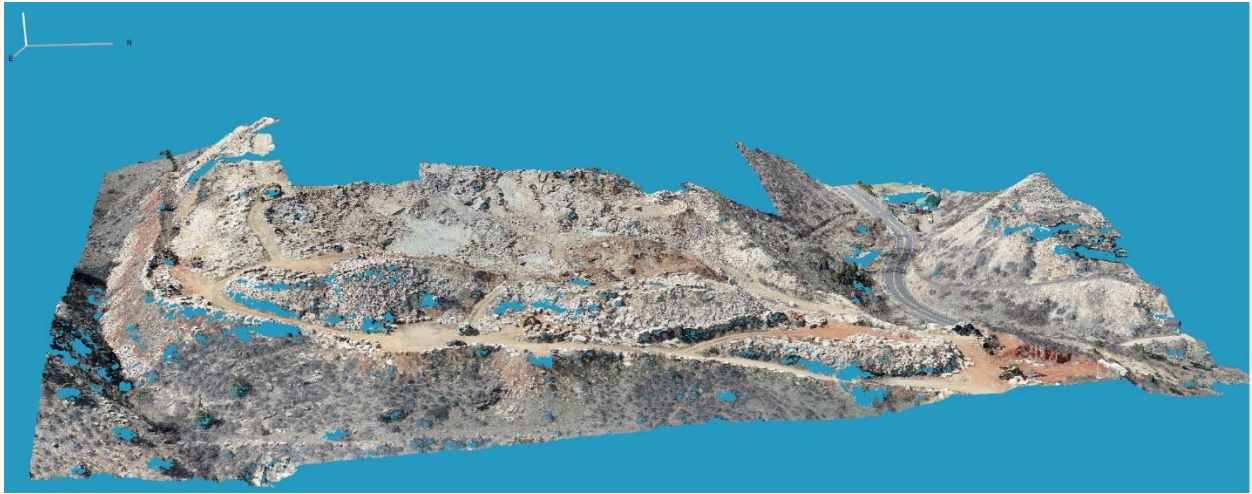


Figure 16: Point cloud generated of the Lyons study site taken on April 1, 2019. Each pixel against the blue background represents a single data point in the point cloud. Data points are colored in the same hue as the associated ground pixel on the orthomosaic (Figure 7) for easy reference between the two- and three-dimensional depictions of the study area.

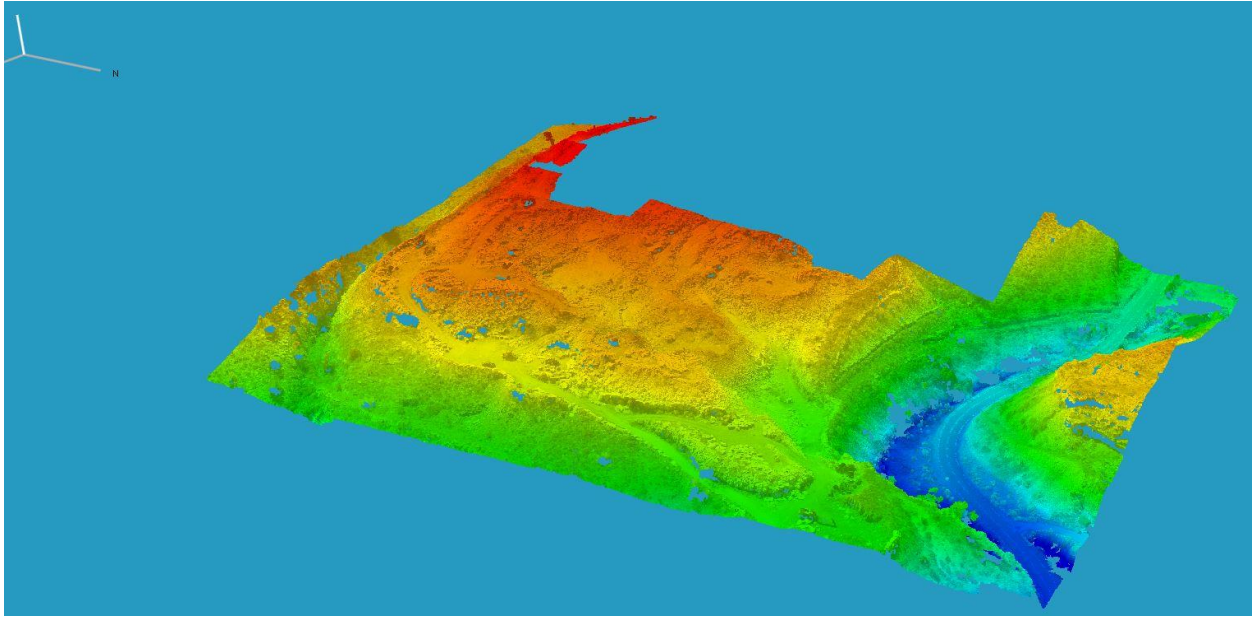


Figure 17: Same point cloud as shown in Figure 16. This example is shaded to show relative height. The highest points are depicted in Red and of 1674 meters above mean sea level. The lowest point in the image is 1604 meters above mean sea level and is depicted in blue.

DIGITAL SURFACE MODELS (DSMs)

Digital Surface Models are the point clouds as seen above, with the addition that they include computed vectors in areas of no data points. While these are an estimation, they can help to create more complete models of the study area.

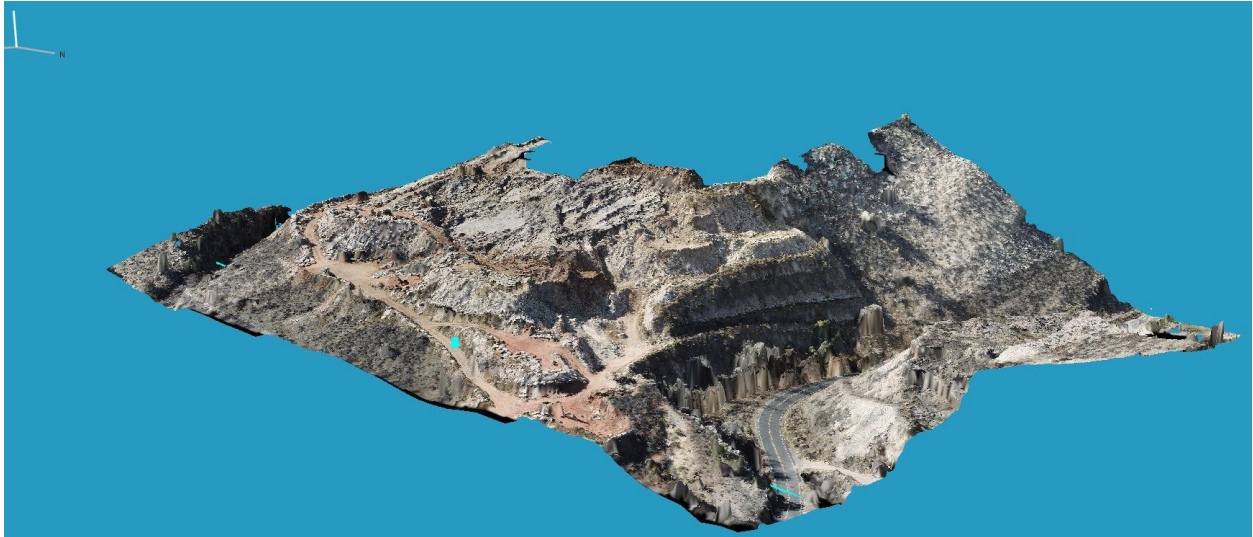


Figure 18: Digital Surface Map of the Lyons study site from the imagery taken on November 10, 2018. The Digital Surface Map is the point cloud with vectors between points of no data to enhance the coherence of the entire image.

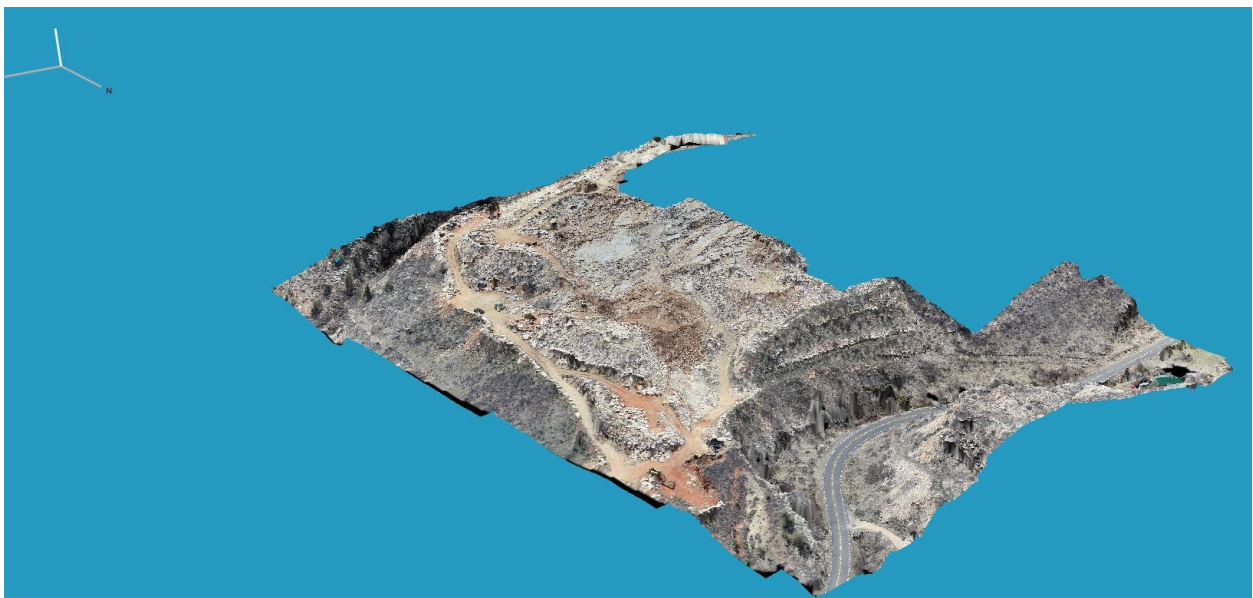


Figure 19: Digital Surface Map of the Lyons study site from the imagery taken on April 1, 2019. The Digital Surface Map is the point cloud with vectors between points of no data to enhance the coherence of the entire image.

DIGITAL ELEVATION MODELS (DEMs)

Digital Elevation Models use contour lines generated by the point cloud as well as point cloud data points between the contour lines to generate a map of the approximate surface elevations of the study area.

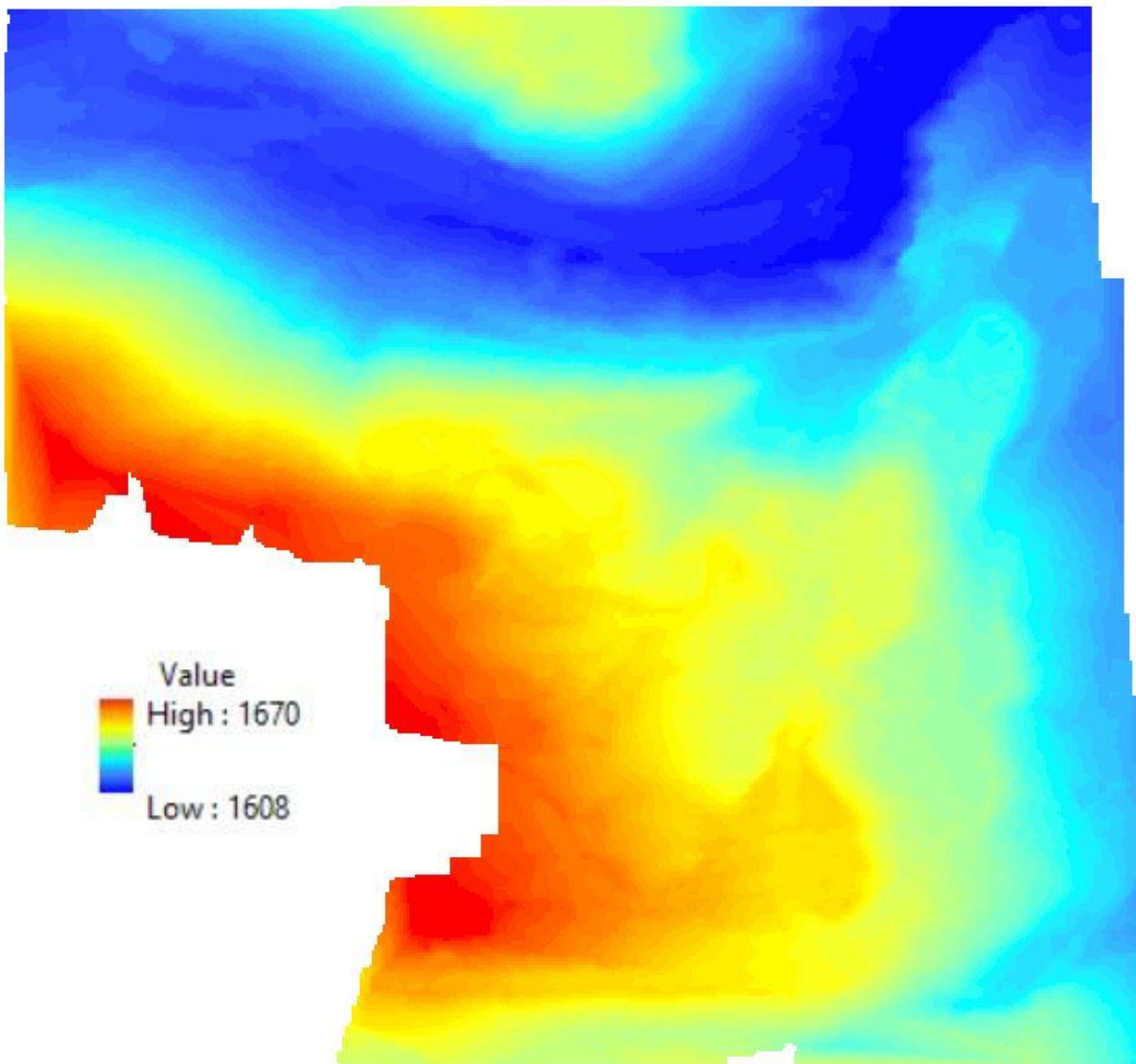


Figure 20: Digital Elevation Map (DEM) taken of the Lyons site on November 10, 2018. The red colors represent the highest elevations (1670 meters) and the blue hues represent the lowest elevations (1604 meters).

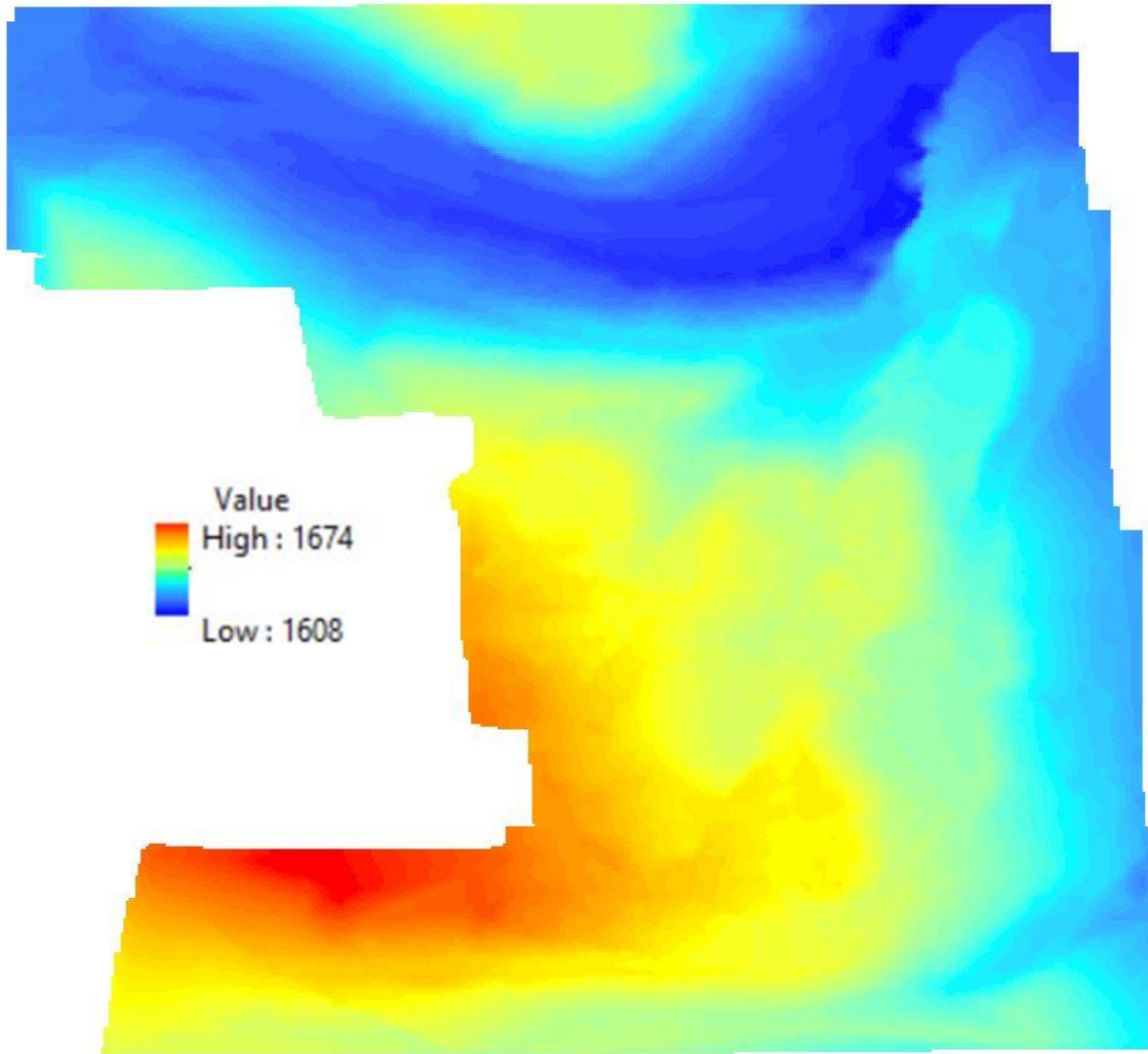


Figure 21: Digital Elevation Map (DEM) taken of the Lyons site on April 1, 2019. The red colors represent the highest elevations (1674 meters) and the blue hues represent the lowest elevations (1604 meters).

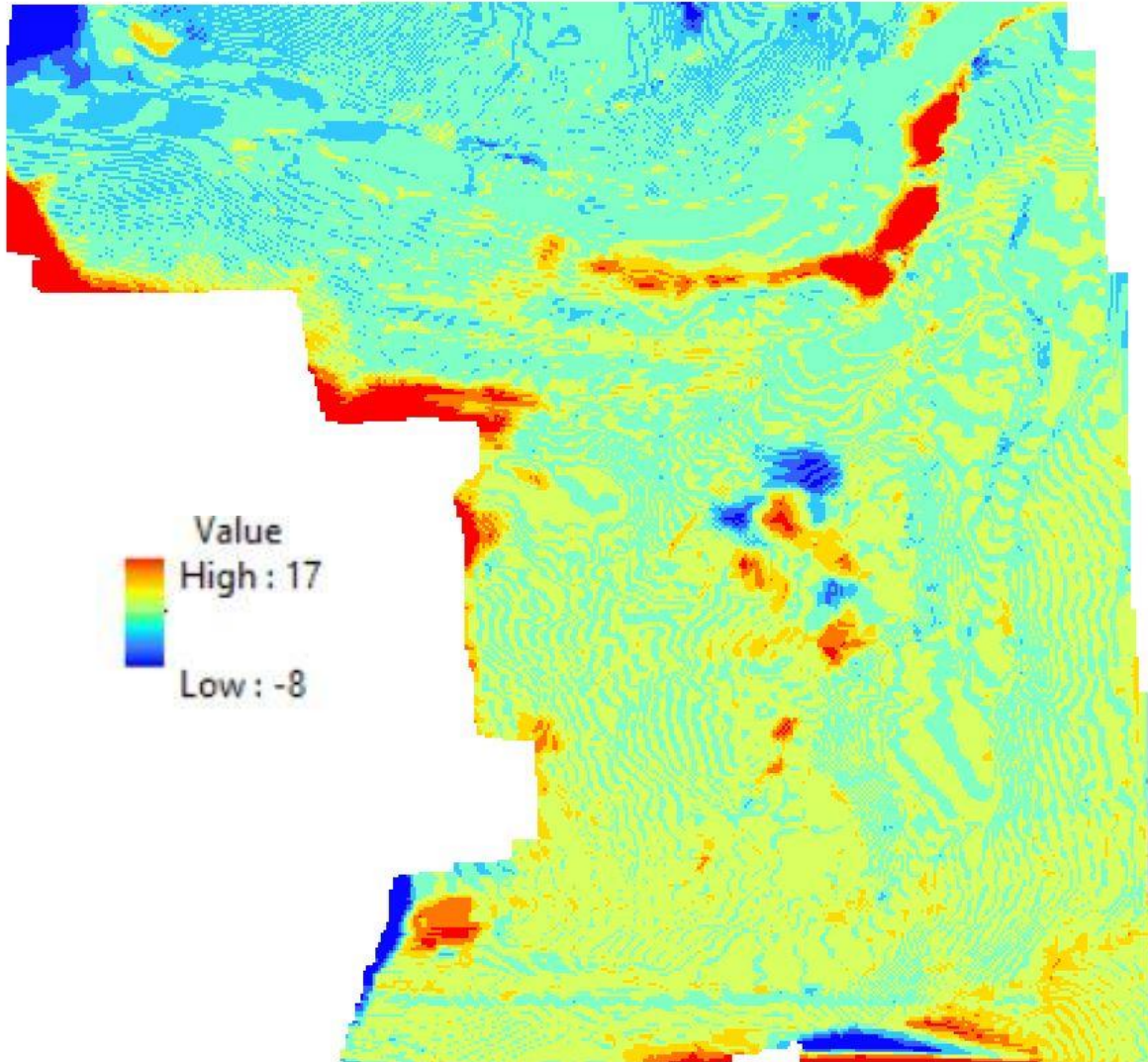


Figure 22: This image depicts the difference in elevation change between the two DEMs. The scale is shown to the left in units of feet. This was completed by subtracting the elevation values of matching pixels between the November and April drone flights, so the blue areas represent elevation gain and the red areas represent elevation loss.

COMPARISON OF InSAR & SFM ON LYONS SITE

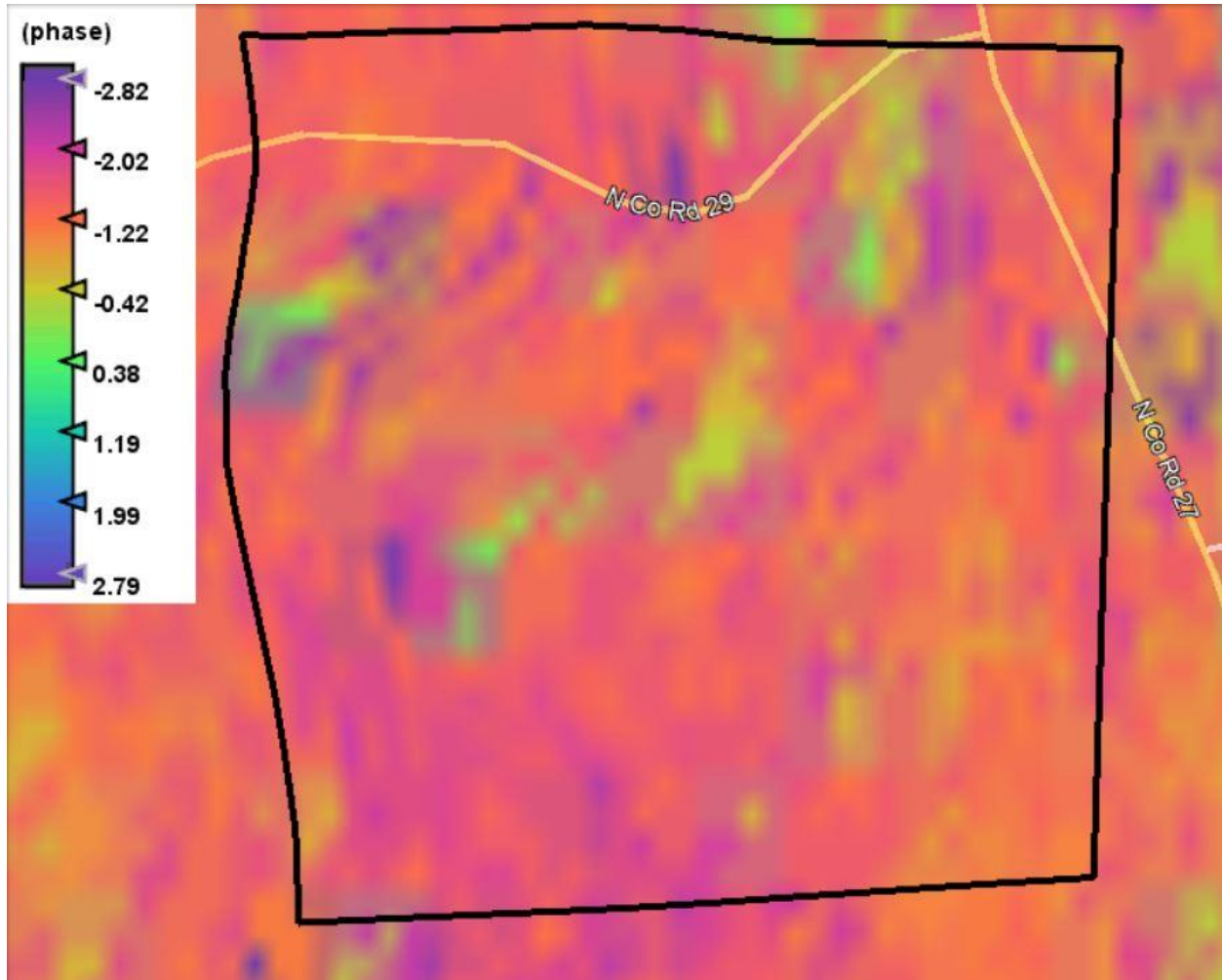


Figure 23: InSAR Interferogram showing the phase of the ESA Sentinel-1A of the Lyons site. Scale is in radians, 2π radians is ~ 5.45 cm of deformation.

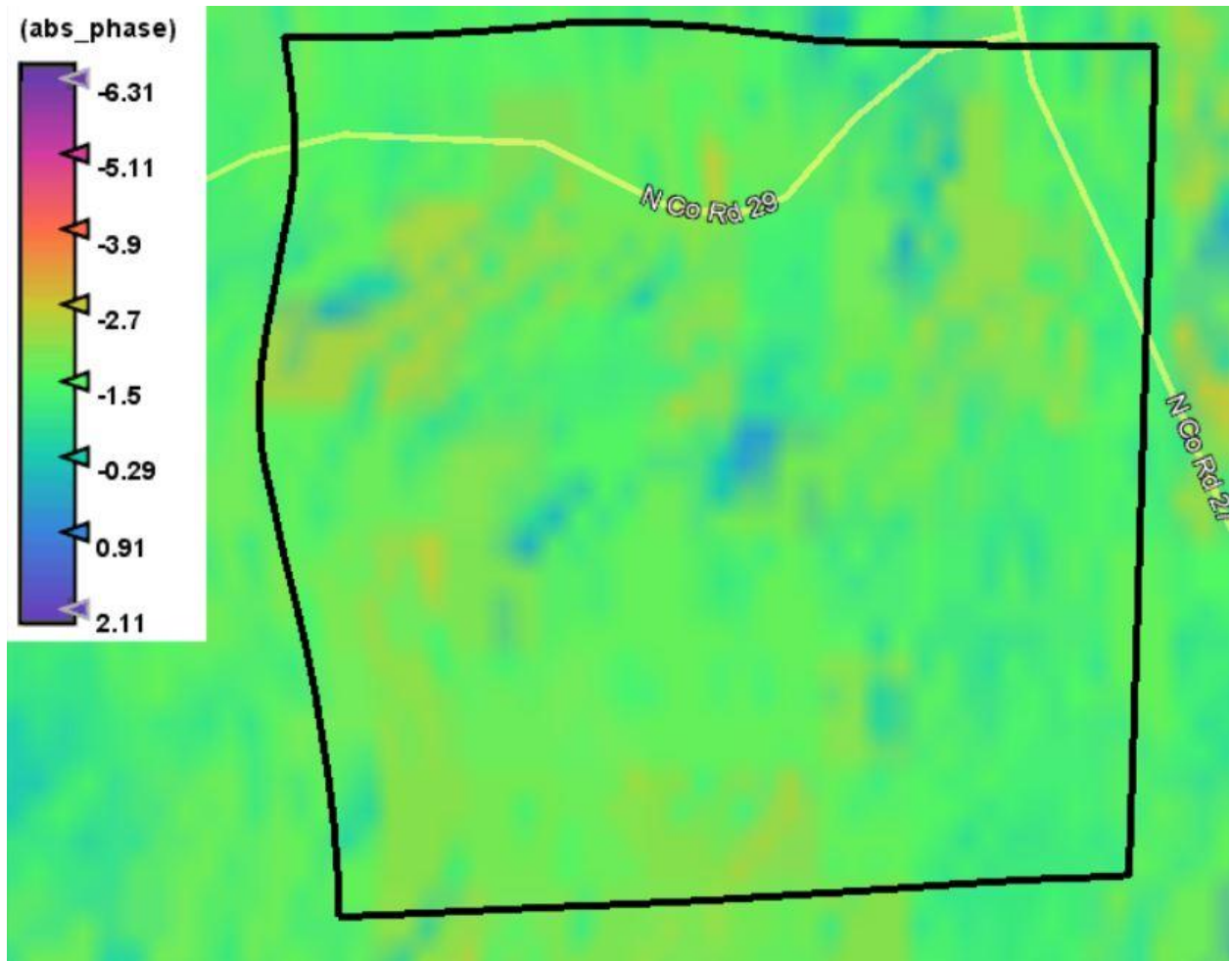
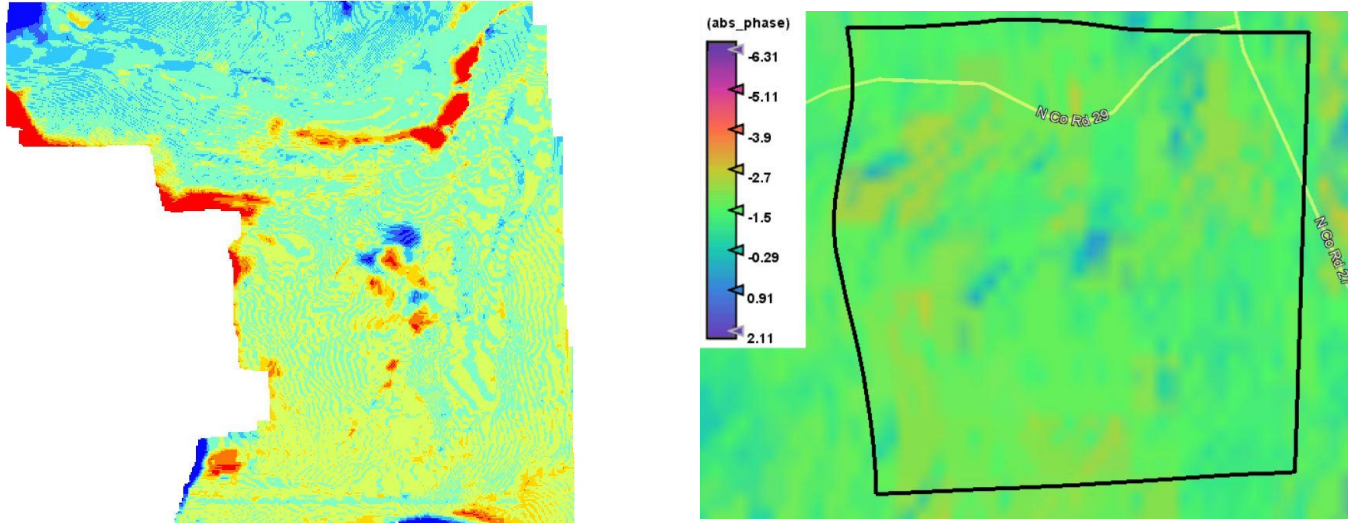


Figure 24: InSAR Interferogram showing the Unwrapped Phase of the Sentinel-1A satellite on the Lyons site. Scale is in radians, 2π radians is ~ 5.45 cm of displacement.



The DEM difference image is on the left and the unwrapped phase of the InSAR on the right. As seen the SFM image (left) has much better spatial resolution but the vertical accuracy is not as exact as the InSAR image on the right which shows gains and losses of millimeters of surface elevation flux.

DISCUSSION

While both the use of Interferograms from InSAR images and Differenced-DEMs from SFM drone imagery have many separate as well as overlapping uses in academic research there are notable differences in the applications which are most right for each platform. In general, as stated by the hypothesis, InSAR-generated interferograms are more appropriate for when either a large area needs to be measured, or vertical displacement accuracy is of the highest priority. On the other hand, SFM-generated DEMs are more proper when a smaller area is being measured, or spatial resolution needs to be maximized to identify small objects. However, there is more to the pros and cons of each image which will be discussed in this section.

COMPARISON OF InSAR AND SFM ON THE LYONS SITE

Both drone imagery and InSAR radar imagery were gathered over the Lyons site with similar times of acquisition so as to be able to compare the two methods on the same study area to eliminate as many unknown variables as possible that would prevent an adequate comparison

if more than one study area was chosen. The images used in this comparison are Figure 22 which is the differenced DEM raster of the two SFM models and Figure 24 which is the unwrapped phase of the InSAR measurements for a similar period (November 17, 2018 to March 29, 2019). Figure 2 is colored such that the blue areas on the image represent elevation gain, whereas the red areas represent elevation loss. The areas of elevation gain (blue) seen in the center of Figure 22 appear to correspond to the pockets of blue pixels in the InSAR image which also correspond to a gain in elevation of the surface. However, these features are harder to detect in the InSAR image because of the large pixel size. Since the pixel size in the SFM image is much smaller we are able to find smaller features of elevation gain. The InSAR image depicts only a few millimeters of displacement in either direction, which is likely due to the result of the InSAR system averaging the displacement in the 5x20 meter pixel so that even the pixels that show the greatest displacement in the differenced DEM, do not show the same displacement in the InSAR interferogram. Thus, we can conclude that for imaging this site, SFM would likely be a more appropriate option than InSAR.

ADVANTAGES OF InSAR-GENERATED INTERFEROGRAMS

As mentioned in the first discussion section, InSAR-generated interferograms tend to be more appropriate for large areas. This is because as a satellite-based system the field of view is exceptionally large so many kilometers in both the x- and y-directions can be gathered very quickly. This supplies a clear benefit for regional scale events such as large tectonic and volcanic events, land subsidence from natural and anthropogenic processes, and monitoring of large areas of sea and ice. Another benefit of InSAR is that the vertical resolution is not only of high-resolution

but is very accurate as well. Since the instrument measures the change in phase between the two images, more precise information can be developed for each ground pixel than other methods of measurement. When corrected for topographic phase and atmospheric effects the accuracy of vertical measurements in InSAR is around 1 mm (MDA, 2019). Combining this along with the centimeter-scale of InSAR sensors (ESA, 2019), InSAR presents the opportunity to obtain extremely exact displacement measurements that could be hard to predict, even with in-situ based observations.

InSAR is also freely accessible on a variety of platforms for academic use such as the ESA's Copernicus Open Access Hub, which allows the data to not only be widely disseminated but also easily accessible for researchers and students. This makes the use of InSAR data useful for those with limited funding and resources, as there are no additional costs associated with the processing of InSAR data as many of the software platforms such as SNAP are free and open-source.

Lastly, since InSAR is a satellite-based measurement with global coverage, research can be conducted at any number of sites regardless of how physically and logistically challenging it may be to access certain sites. This is particularly helpful for research involving geohazards such as earthquakes, volcanoes, sinkholes, and tsunamis, as well as for monitoring ground activity over areas with land-access issues such as private properties, or hostile territories.

LIMITATIONS OF InSAR-GENERATED INTERFEROGRAMS

However, InSAR is not a perfect system for all applications and there are many constraints and disadvantages involving InSAR which may lead a researcher to explore other remote sensing platforms.

First, ground resolution is often not particularly good on InSAR products especially the free or affordable products. The resolution used by the Sentinel-1 satellite when in IW mode is 5x20 meters which means that any feature contained within that pixel that shows distinct displacement may be adulterated in phase value by the surrounding topography. While the Sentinel-1 system may achieve up to 5x5 meter resolution in the SM mode, this is often nowhere in comparison to drone images which often have pixel resolutions measured in the inches or even centimeters. Additionally, these high-resolution images are not collected globally and are only imaged for specific events or by special request from academic groups so obtaining this high-resolution imagery is much harder. Certain satellites such as the TerraSAR-X mission allows users to request and/or purchase InSAR images with up to a 1-meter resolution, these can often cost upwards of a few thousand dollars, which may be out-of-reach for many research groups, especially if multiple images need to be collected of one area.

Next a great deal of corrections is needed to create accurate interferograms which require a significant level technical competency. Not only does one need to be able to navigate and effectively use the program of choice for the InSAR process, but other computer skills such as navigating complex directories, editing text files, and running executables through a console are required. This is in addition to the knowledge of sensor physics that are required to be able to correct for atmospheric and terrain influence on the radar images.

Lastly, users of InSAR are restricted by the temporal conditions which are external to the analyst's controls. InSAR using the Sentinel-1 sensor has a maximum period of 6 days, which means the highest frequency a given spot on the earth can be sensed is 6 days. However, when using the 6-day period this is accomplished through the use of two separate satellites, Sentinel-1A and Sentinel-1B which have slightly varying orbits. In certain geographical locations the orientation of these orbits does not line up exactly and thus an interferogram cannot be computed with that image pair. When using the same satellites, the images will be of the same orientation as they are taken on the same orbit track, but the period reduces to 12 days. This means that for most interferograms the highest resolution between images is 12 days, but objects or areas of elevation which may oscillate between the period will not be accounted for in the final images. Another constraint of the temporal resolution is that it is not possible for the analyst to control exactly when the images are captured.

ADVANTAGES OF SFM-GENERATED DEMs

One of the main benefits of using SFM-generated DEMs, especially when using drones as a platform is that the spatial resolution of the images tends to be exceedingly high, often as high as ~1-5 inches. A high resolution allows both the analyst and end user to be able to effectively identify surface changes of small features which would not be able to be identified on other systems such as in InSAR. This makes SFM a smart choice for use on areas which have small-sized human impacts such as excavation and construction, where objects less than a few square meters may rapidly change in elevation.

Another benefit of using drones is that the temporal resolution can be very great. While it is often typical for the period of an InSAR satellite to be between a week and a fortnight. Drones can be flown soon after the first images are collected and transferred to the software or multiple

drones may be able to simultaneously operate with careful flight planning. This makes drones especially useful for measuring displacement, whenever desired especially for events which may be short in duration.

CHALLENGES OF SFM-GENERATED DEMs

One of the most apparent challenges with using SFM-generated DEMs from drone imagery is the accuracy of the measurements. Since the software program is using mathematics to predict the elevation of the object or the area, the elevation values are an estimate and do not reflect a true elevation or distance measurement between the area and the sensor. This can be mitigated by using ground control points (GCPs). Using a GCP the software will be able to calibrate the detected elevation values relative to a geographic position of known absolute elevation. This is important as there is an accuracy error in the GPS system used by drones. The phantom drones used in this study have vertical accuracies around 0.1 meters and horizontal accuracies of around 1.5 m. This means that there could be some variation in the actual geographic position between the detected and actual pixels on the ground. However, this error is far less than the pixel size of the InSAR systems we are comparing drones too, however the vertical accuracy is far better in SAR systems.

Another limitation of using drones is that you must have adequate access to the land you are trying to survey. I have defined two main factors of land access in my research that are needed for academic drone surveys: Physical Land Access (PLA) and Legal Land Access (LLA). PLA is the first and foremost access needed to conduct research which is the ability for a research party to be able to access the study area to set up, launch, collect, land, and upload the collected data. Urban and Suburban areas are usually the easiest for this as there is ample access for transportation and staging. These areas are followed by rural areas, which have limited transportation infrastructure

and are often defined by large expanses of land, usually privately owned. This was the case for our study area near Lyons and Loveland, CO and involved both additional considerations for flight planning and searching for a spot to conduct takeoff and landing operations. This issue of PLA is most important however when considering research in inhospitable environments such as the Arctic, Deserts, Remote Wilderness, or areas around Geohazards. In these cases, it may not be possible to deploy a drone due to limitations of drone altitude ceiling or battery life, though this may change as technology continues to advance, especially in the drones geared towards academic and professional use.

The next issue of land access is that of Legal Land Access or LLA. This is important because as drones are becoming ever more popular, so are the pressures for legislation on the local, state, and federal levels to restrict their operation for both professional and recreation use. The current political climate is relatively neutral between the drone operators and land owners but there is the potential for altitude or areal restrictions over certain geographic features for either privacy or security reasons. Thus, the political climate may change such that it becomes harder (or possibly easier, though unlikely) to survey areas of private property without landowner approval. The other issue is that there is the potential for costly equipment replacement for the instance that a drone crashes and it is not on physically or legally accessible land. In this case both the instruments, and usually data are lost in this scenario. This is not the case for InSAR as the satellite images all land regardless of physical or legal status.

Table 1	Pros	Cons	Best Applications
InSAR	<ul style="list-style-type: none"> • High vertical accuracy • Large imaged area • Accessible data • No additional equipment necessary • Global Coverage 	<ul style="list-style-type: none"> • Poor ground resolution • Technically intensive processing • Defined temporal resolution of 6-12 days max. 	<ul style="list-style-type: none"> • Monitoring of large or regional scale events • Determination of small-scale (cm) elevation flux • Time-series studies
SFM	<ul style="list-style-type: none"> • High spatial resolution • Feature Identification • High temporal resolution • Minimal processing required 	<ul style="list-style-type: none"> • Influence of drone GPS error • Poor vertical resolution (meter scale) • Must have adequate access to land for survey 	<ul style="list-style-type: none"> • Monitoring events which happen at short notice • Identifying changes of elevation in small features • Integration with other DEM-based observations such as LiDAR

CONCLUSION

In summation, while InSAR and SFM can be used on a large variety of applications, their strengths and weaknesses must be identified and used to fit the appropriate method with the type of research being conducted. The easiest differentiator between InSAR and SFM is the scale of the project and resolution needed. For large and/or regional scale products that seek to quantify broad-wavelength deformation and displacement with the vertical accuracy being essential to the final project, InSAR is the obvious choice. However, if the study area is considerably smaller and distinct features such as structures, vegetation, or anthropogenically altered environments need to be identified, SFM offers a better method, in exchange for vertical accuracy. In a separate sense, SFM-generated DEMs from drone are the best method for determining whether the surface is being

displaced in either direction, and by relatively what amount. If the priority is to find the exact displacement to this highest degree of accuracy, use of InSAR or other SAR-based methods would be more appropriate.

These findings are important to the scientific community, because the strengths and weaknesses highlighted in this research can help researchers and scientists to confirm whether or not the use of InSAR or SFM from drones is appropriate to their research goals. This research also lays the foundation for investigating the use of both systems in combination, to play on the advantages of both systems to advance accuracy and feasibility of future research in the geosciences and surface processes which is described in the following section.

FUTURE RESEARCH

Future research is needed to be conducted on the use of SFM in conjunction with studies that already involve the use of InSAR or vice versa. In projects that already involve the use of InSAR, SFM could add an extra dimension of certainty when specific localized areas of rapid deformation are detected (associated with a steep lateral gradient of interferometric fringes). When SFM from a drone is used in these localized areas a researcher can gain a better understanding of what is the average relative movement of the object or area in focus. Similarly, InSAR can be used in SFM to better quantify the average surface displacement. While SFM does an excellent job at identifying surface elevation flux in features which may normally become washed out by the large pixel size of InSAR. Using interferograms can give insight to researchers on the overall trend of surface elevation flux. This is especially true for large time-series analysis as the cost per single image acquisition tend to be much less for InSAR than using a drone (due to organization, transportation, and labor involved with conducting drone flights).

It could also be particularly helpful for scientists to develop a model or toolbox for remote sensing software to easily integrate these two measurement options together. By using georeferencing, feature-matching, change detection, and band math algorithms (among other features), there is enormous potential for future technological advancements that progress the usability of the two methods in combination with one another.

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