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**Technical Note 448**

# **An Overview of Data Collection and Analysis Methods for Calculating the Volume of Mine Materials**

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# Abstract |

The purpose of this technical note is to assist Bureau of Land Management employees in determining which data collection methods are most appropriate to calculate the volumes of remaining or removed mining material at a site. This tech note primarily provides an overview of data collection methods for calculating the volumes of surface mineral material remaining at abandoned mine land sites or the volumes of material removed from gravel or sand sites. Data analysis methods are also provided. The goal of this tech note is to assist BLM field staff in (1) understanding the available data collection methods and (2) determining the most appropriate data collection method for their project. The data collection methods highlighted for deposits include

Global Positioning System (GPS), laser scanning, photogrammetry, analog measurements, drilling, trenching, geophysics, landscape interpolation by GPS, and aerial photography. The data collection methods highlighted for pits include GPS, laser scanning, photogrammetry, analog measurements, preexisting data, aerial photography, “flat cap,” and landscape interpolation. Each data collection method is rated qualitatively based on the following criteria: applicability, level of effort, reliability, and others. The data analysis methods highlighted in this tech note include digital terrain model software, average end area, and geometric calculations.

# 1. Introduction |

The primary audience of this technical note is the Bureau of Land Management's (BLM's) Abandoned Mine Lands and Mineral Materials Programs. This tech note primarily provides an overview of the data collection methods for calculating volumes of remaining or removed material at mine or mineral sites. Data analysis methods are also discussed.

As this is an overview of commonly used data collection methods, this tech note does not provide a quantitative comparison of the different methods. However, the tech note includes summaries of qualitative descriptions regarding accuracy, applicability, level of effort, reliability, cost, and other metrics of each method. This tech note will assist staff in determining the appropriate data collection method for their project.

## 1.1 Why Are Volume Calculations Necessary?

The BLM's Abandoned Mine Lands Program addresses the physical safety and environmental hazards at abandoned mine sites. While planning remediation options for a site, an accurate calculation of the volume of waste rock or tailings piles can refine the remedy alternatives and provide more precise cost estimates for the remedy alternatives.

In the Mineral Materials Program, the BLM inspects and monitors the activity of active mineral operations (e.g., sand, gravel, stone) to verify that the amount of mined material is properly reported. Accurate volume calculations assist the solid minerals staff in reliably and correctly validating the production reports and ensuring proper royalty payments.

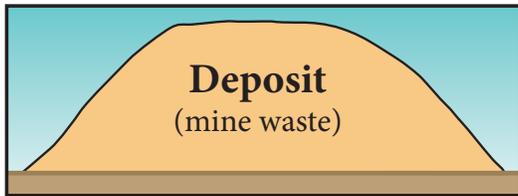
Whether a site contains several tailings deposits or is a large gravel pit, the data collection methods presented in this tech note are appropriate at either type of site to calculate volumes for the material that remains or for the material that has been removed.

## 1.2 Volume Calculations: An Overview

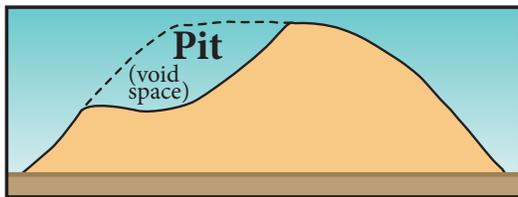
Volume calculations consist of two phases: data collection and data analysis. The data collection phase involves taking measurements of the target object (e.g., tailings pile, gravel pit). This phase may include researching historical sources of data, such as aerial photography. In the data analysis phase, the information from the data collection phase is processed to calculate volumes. Most analytical methods rely upon the assistance of computers to calculate volumes, though there are exceptions in which hand-based calculations are sufficient.

## 2. Data Collection Phase |

The data collection phase, the first phase for calculating the volume, involves taking measurements of the target object (e.g., talings pile, waste rock dump, gravel pit, fill material). For deposits, volume calculations help determine the remaining amount of earth material or mine waste (see Figure 1). For pits, volume calculations help determine the “void space,” which represents the amount of material that has been removed (see Figure 2). For these volume calculations, staff collect and compare two “planes” of information using the geometric object concept.



**Figure 1.** Representation of the volume of remaining mine waste



**Figure 2.** Representation of the volume of removed material

### 2.1 Geometric Object Concept

Two planes of analysis are required for calculating volumes of deposits and pits. One plane can be accurately measured, while the other can only be estimated. Calculating volumes for deposits and pits differ between which plane is measured and which plane is estimated. Table 1 presents the target objects and the measured and estimated planes.

**Table 1.** The exposed face, measured plane, and estimated plane of deposits and pits

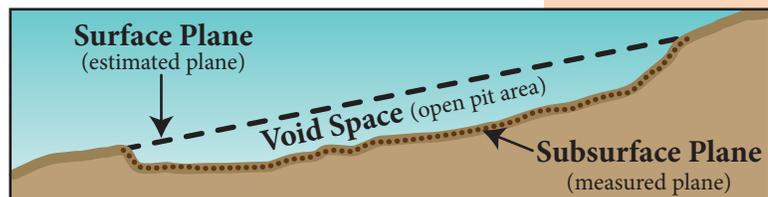
Target Object	Exposed Face	Measured Plane	Estimated Plane
Deposit	surface of deposit	surface plane	subsurface plane
Pit	bottom of pit	subsurface plane	surface plane

For deposits, the goal is to calculate the volume of the remaining amount of earth material or mine waste. The area and location of the surface plane can be accurately measured. However, the subsurface plane, or the contact area between the deposited material and a reference material (e.g., undisturbed earth), is frequently estimated (see Figure 3).



**Figure 3.** Surface and subsurface planes of deposits

For pits, the goal is to calculate the volume of the void space representing the material (e.g., sand, gravel, stone) removed from the pit. The subsurface plane of the void space is the exposed earth of the pit and can be accurately measured. The surface plane of the void space is the earth’s surface prior to disturbance/excavation and is typically estimated (see Figure 4). In some cases, preexisting data are available.



**Figure 4.** Surface and subsurface planes of pits

**A note on location:** Spatial information (e.g., latitude/longitude) is not necessary to calculate volumes. However, spatial information is necessary to determine the object’s exact location in a GIS environment. Typically, this is achieved through the use of a Global Positioning System (GPS). Local coordinate systems, such as distance from a known marker, can also be used.

**A note on resolution:** Appropriate resolution should be determined prior to the

start of any project. Several factors, such as target object size, data collection method, and intended use of the resultant volume calculations, will determine the appropriate resolution.

## 2.2 Data Collection Methods

This tech note presents the data collection methods in two sections: data collection methods for deposits and data collection methods for pits. While many of the same methods are applicable for both deposits and pits, certain methods perform better for deposits and others for pits.

Each data collection method is qualitatively described using the following criteria: accuracy, applicability, level of effort, reliability, specialized knowledge, cost, and overall ranking for both deposits and pits. The criteria are applicable to the data collection methods as follows:

- a. **Accuracy** - The potential of the data collection method in measuring the target object's true volume.
- b. **Applicability** - The performance ability of the data collection method for measuring a particular pit or deposit. This criterion takes into account the physical location (setting), size, and shape of a target object and assesses how well the method can be used for a site.
- c. **Level of Effort** - The amount of labor, time, and resources required to perform the data collection method. Intrusiveness, or the amount of destructiveness or disruptiveness of the method, is also considered.
- d. **Reliability** - The likelihood that the collected data will successfully calculate volumes in the analysis phase.
- e. **Specialized Knowledge** - The technical or professional knowledge required to collect or interpret the data.
- f. **Cost** - The monetary resources required to perform data collection. BLM travel ceiling dollars are noted if applicable. All cost estimates are based on incurred costs at representative and/or existing sites throughout BLM-managed lands.
- g. **Overall** - An overall ranking that factors in all of the other variables.
- h. **Defensibility** (pits only) - The likelihood that the resultant data and models are commonly accepted for production verification in salable mineral operations.

## 3. Data Collection Methods for Deposits |

Typical abandoned mine features requiring volume calculation include tailings piles or waste rock piles. The surface planes of these deposits can be accurately measured through several methods. The subsurface planes of these deposits are generally more difficult to accurately measure and result in the source of greatest error in final volume calculations.

### 3.1 Surface Plane Measurements

The surface planes of deposits can be accurately measured, often to millimeter precision. In this tech note, the data collection methods for measuring the surfaces of deposits include GPS, laser scanning, photogrammetry, and analog measurements. This section presents these data collection methods and provides qualitative ratings, from very low to high, regarding their performance at measuring the surface planes of deposits. Overall ratings of data collection methods include poor, average, good, or very good.

#### 3.1.1 Global Positioning System

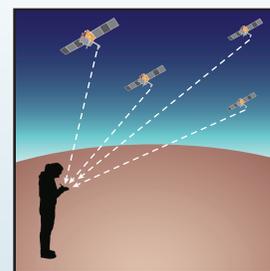
GPS provides location information based on transmissions from a network of satellites orbiting the earth. GPS measures the surface of a deposit in two ways. First, a grid of user-defined resolution delineates point locations on the surface of the deposit. This information is then interpolated into a smooth surface containing the horizontal (X, Y) attribute information with the vertical (Z) elevation values. The second way is to collect continuous linear transects over the surface of the pile. The X, Y, and Z values for the surface of the pile are interpolated from the lines. The two types of GPS include standalone and differential.

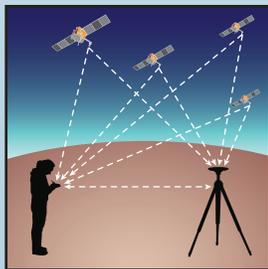
##### 3.1.1.1 Standalone GPS

A standalone system involves the use of a handheld unit that processes signals from at least four satellites to calculate location information.

- a. **Accuracy - Low**  
The accuracy of the resultant model relies on the accuracy and resolution of the collected data. Standalone systems provide accuracy within a range of  $\pm 2$  to 5 meters. The use of an external antenna can improve the accuracy by  $\pm 1$  to 2 meters. Generally, this amount of accuracy is not sufficient to calculate volumes for small to medium deposits.<sup>1</sup>
- b. **Applicability - Low**  
The main constraint with using GPS is those collecting the data must traverse the surface of the deposit. Safety concerns regarding slips, trips, and falls or the large dimensions of deposits often outweigh the benefit of using GPS to collect surface information. Additionally, the applicability of standalone GPS is limited to very large deposits in which the level of accuracy is insignificant compared to the size of the deposit.
- c. **Level of Effort - Medium**  
The required level of effort for collecting GPS data depends on the size of the deposit and the desired resolution of the surface plane model. As the deposit size and desired resolution increases, the amount of time and effort increases.
- d. **Reliability - Very Low to Medium**  
Depending on the size of the deposit, the reliability of standalone GPS is very low (for small deposits) to medium (for large to very large deposits) for successfully calculating a surface plane. Standalone GPS reliability increases to medium when the deposit is so

<sup>1</sup> See glossary for definitions of deposit and pit sizes.





large that an accuracy range of  $\pm 2$  to 5 meters is insignificant compared to the overall size of the target object. The reliability is very low for smaller deposits because an accuracy range of  $\pm 2$  to 5 meters significantly affects the confidence and accuracy of the resultant surface and volume.

- e. **Specialized Knowledge - Low**  
Many individuals are familiar with the operation of standalone GPS units for data collection. Individuals should be properly trained in configuring GPS devices prior to collecting data.
- f. **Cost - Low**  
Generally, standalone GPS units are inexpensive, often between \$400 and \$3,000. However, accuracy and desired model resolution should factor into which GPS device to use.
- g. **Overall - Average**  
A standalone system is a relatively simple method for BLM staff to collect surface data with minimal costs.

### 3.1.1.2 Differential GPS

A differential GPS system involves the use of a stationary base station and rover combination, which provides much higher positional accuracy than standalone GPS. Data collected in the field are processed and corrected afterward using information published by the Online Positioning User Service to improve the accuracy. Differential GPS can be performed in the field and corrected nearly instantaneously using radios known as “real time kinematic” (RTK).

- a. **Accuracy - High**  
The accuracy of the resultant surface model relies on the accuracy and resolution of the collected data. Differential GPS systems can achieve subcentimeter accuracy. This can result in a very accurate surface measurement and is often more than enough information to calculate a reliable surface model for deposits. Higher density grids (increased number of total points on the surface) or shorter

distances between linear transects result in a higher resolution surface model with greater accuracy.

#### b. **Applicability - Medium**

The main constraint with using GPS to collect data is that those collecting the data must traverse the surface of the deposit. Safety concerns regarding slips, trips, and falls or the large dimensions of deposits often outweigh the benefit of using GPS to collect surface information. Differential GPS is applicable for all sizes of deposits that do not pose safety hazards and in which deposit dimensions do not interfere with data collection.

#### c. **Level of Effort - Medium**

The required level of effort for collecting GPS data depends on the size of the deposit and the desired resolution. Since GPS data is collected from the location of the rover, the deposit must be traversed. The larger the deposit, the more time and effort required to collect information. Also, the higher the desired resolution, the more time required for collecting data. It is necessary to consider scale when deciding the resolution of any deposit.<sup>2</sup> Differential GPS systems also have an additional time requirement associated with setting up and taking down a base station.

#### d. **Reliability - Medium to High**

The resolution of collected data points determines whether the reliability is medium or high. The higher the resolution, the higher the reliability.<sup>2</sup>

<sup>2</sup> When determining the appropriate resolution for any project (e.g., whether to use a method that provides subcentimeter resolution or a method that provides meter resolution), take into account the size of the object and goal of the project. For example, subcentimeter resolution and a distance of 2 centimeters between GPS data collection points is likely overkill for calculating a volume of a tailings deposit that measures 100 meters long in two directions and 50 meters tall and will ultimately be evaluated by engineers in cubic yards and transported by the truckload.

e. **Specialized Knowledge - Medium**  
Setup, operation, and data transfer for differential GPS requires some training. Individuals require the ability to troubleshoot communication issues between the base and the rover in the field and knowledge of vendor-specific software protocols.

f. **Cost - Medium**  
RTK differential GPS systems cost between approximately \$10,000 and \$30,000. Instead of purchasing an RTK system, users can also rent one. Startup costs for non-RTK differential GPS systems are lower but typically require yearly software fees for incorporating data processed by the Online Positioning User Service. There is a very low annual equipment maintenance cost, often \$0, associated with RTK differential GPS systems. For BLM staff, the National Operations Center (NOC) in Denver, Colorado, maintains two RTK differential GPS systems. The NOC can train individuals on the operation of the units or perform the data collection if necessary. Travel ceiling implications apply when considering hands-on training or NOC data collection. However, shipping costs for the equipment are minimal. The largest cost associated with data collection via RTK differential GPS is typically travel costs (transportation, per diem).

g. **Overall - Good**  
Although this method produces highly accurate and reliable results, it should only be used if the proper expertise is available.

### 3.1.2 Laser Scanning

Laser scanning, also referred to as light detection and ranging (LiDAR), operates on the principle of measuring the amount of time it takes a pulse of light to reflect off an object and back to the scanner. This provides a measurement of the distance between the scanner and object, which can create scaled 3D models of any object off of which

the light reflects. The datasets are generally referred to as point clouds, with each measurement representing a point in space. LiDAR captures datasets from the ground (terrestrial laser scanning) or from the air (airborne laser scanning).

#### 3.1.2.1 Terrestrial Laser Scanning

In terrestrial laser scanning, a laser scanner collects data from a stationary location on the ground. Sometimes, to capture an entire deposit with terrestrial laser scanning, multiple data collection locations are necessary.

a. **Accuracy - High**

Laser scanners can accurately measure the shape and size of deposits to decimeter resolution. External reference control (e.g., GPS) is required to georeference the location of the resultant model. However, laser scanners can create accurately scaled models without external reference.

b. **Applicability - Medium to High**

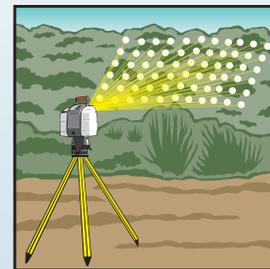
A laser scanner in a stationary location can only collect data for the portion of the deposit in its line of sight. The scanner must be moved to different locations around the deposit to create a complete model. For simple, smooth deposits, the applicability of laser scanning is high. For complex deposits with topographic features (e.g., undulations) that hide portions of the surface from the scanner's viewshed, the applicability drops to medium.

c. **Level of Effort - Low to Medium**

The level of effort is low for simple deposits. Generally, a laser scanner is placed in more than one location to capture the entire exposed surface of the deposit. The level of effort rises to medium with greater deposit complexity and size.

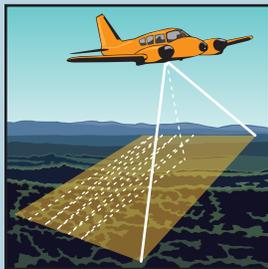
d. **Reliability - High**

The surface plane created using laser scanning is highly reliable. The data collected by the laser scanner typically has a low amount of error



and is accurate and precise. Reliability increases when the resolution and number of data collection locations increase.

- e. **Specialized Knowledge - Medium**  
Most individuals require training in the operation of LiDAR equipment and data processing. However, advances in the LiDAR field have resulted in “user friendly” LiDAR instrumentation and data processing software packages. Once trained, data collection and processing require little additional specialized knowledge.
- f. **Cost - Medium to High**  
Laser scanner costs range from approximately \$40,000 to \$60,000 depending on the model. This does not include training costs. Annual maintenance costs are very low, often \$0.
- g. **Overall - Good**  
Although this method requires several data collection locations, which increase the amount of time in the field, the data are reliable.



### 3.1.2.2 Airborne Laser Scanning

Airborne laser scanning uses laser scanners that are mounted on manned or unmanned aircraft. The laser scanners collect data when the aircraft flies over individual site locations. Unlike terrestrial laser scanning, the sensor is constantly in motion, which prevents the user from having to physically move the laser scanner to multiple locations around the deposit.

- a. **Accuracy - High**  
Laser scanners can accurately measure the shape and size of deposits to decimeter resolution. External reference control (e.g., GPS) is required to georeference the location of the resultant model. However, laser scanners can create accurately scaled models without external reference.
- b. **Applicability - High**  
Airborne laser scanners can capture

nearly every deposit that is visible from the air.

- c. **Level of Effort - Medium**  
Airborne laser scanning is rated medium due to the contracting or coordination requirements for obtaining flight clearances and aircraft. The NOC currently does not maintain an unmanned aerial system (UAS)-ready laser scanner, so contracting is necessary.
- d. **Reliability - High**  
The surface plane created using airborne laser scanning is highly reliable. The data collected by the laser scanner typically has a low amount of error and is accurate and precise.
- e. **Specialized Knowledge - High**  
Airborne data collection via aircraft requires a licensed and certified pilot, a plane, and special equipment. UAS data collection requires a pilot certified by the Department of the Interior to operate the UAS.
- f. **Cost - Medium**  
An airborne data collection event can cost between \$30,000 and \$35,000. This amount is cost prohibitive if only one deposit is captured. However, if multiple deposits lie within a defined geographic radius, the cost per site decreases.
- g. **Overall - Average to Good**  
Terrestrial laser scanning is not as efficient at capturing the surface of deposits because it requires data to be collected from stationary points around the surface, potentially increasing field time. For airborne laser scanning, this time or logistical impediment is removed, but the overall cost of data collection is greater. Ultimately, laser scanning is a reliable data collection method for deposits.

### 3.1.3 Photogrammetry

Photogrammetry calculates a 3D model of surfaces using adjacent, overlapping

photographs. This data collection method results in very accurate 3D models by using effectively captured photographs of an object. The two methods of collecting photogrammetric images include ground based and airborne.

### 3.1.3.1 Ground-Based Photogrammetry

Ground-based photogrammetry involves capturing photographs from either the photographer's eye level or from an object extended up from ground level (e.g., monopod, cherry picker).

#### a. Accuracy - High

Photogrammetry can produce surface models that accurately represent the shape and size of deposits. With current photographic technology, this can equate to subcentimeter resolution. External reference control (e.g., GPS) is required to georeference the location of the resultant model. However, photogrammetry can create accurately scaled models without an external reference.

#### b. Applicability - Medium

In order to create an accurate surface model, the photographer must capture the entire deposit in overlapping photographs. This requires the photographer to move the camera around the deposit and adequately capture the surface. The greater the complexity of the topographic features or the greater the size of the deposit, the more difficult and less applicable this method becomes. This is due to the limitations of the photographer in reaching the necessary vantage points to adequately capture the deposit stereoscopically, or in stereo.

#### c. Level of Effort - Low to High

Photographers can capture small or simple deposits stereoscopically in less than an hour. Larger deposits or complex topographic features on the surface of deposits can prove challenging and time consuming, often requiring multiple days to capture stereoscopically.

#### d. Reliability - High

Assuming the photographer collected effective photographs, surface models derived from ground-based photogrammetry are very reliable. The models fail when effective photographs of the deposit have not been captured, which occasionally occurs when collected from the ground.

#### e. Specialized Knowledge - Medium

If not already known, initial training of how to capture objects in stereo is required. For complex deposits, a higher level of understanding of photogrammetric principles is recommended, but not always necessary, for successful 3D models.

#### f. Cost - Low

A fixed-aperture digital single-lens reflex (DSLR) camera, approximately \$300, is the minimum recommended technology for capturing effective photographs. Higher megapixel, fully programmable DSLR cameras (which range from \$800 to \$6,000) are more reliable. Camera and travel costs are the only required costs, besides labor hours for photogrammetric data collection.

#### g. Overall - Poor to Good

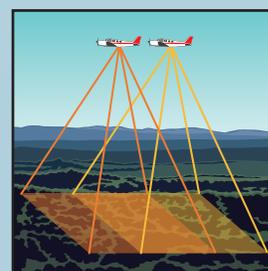
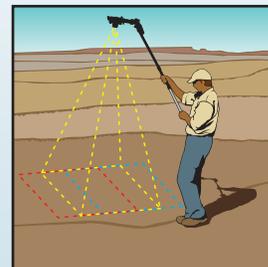
Ground-based photogrammetry is a good method for collecting data for simple, small- to medium-sized deposits. It can adequately capture accurate information about large or complex deposits but requires a greater level of effort. This data collection method can also fail for larger or complex deposits.

### 3.1.3.2 Airborne Photogrammetry

Airborne photogrammetric data collection involves fixing a camera to an aircraft and collecting stereoscopic photographs from the air. These aircraft can include a fixed-wing or rotary-wing passenger aircraft or a UAS. The airborne aspect of this method eliminates vantage point issues associated with ground-based photogrammetry.

#### a. Accuracy - High

Photogrammetry can produce surface





models that accurately represent the shape and size of deposits. With current photographic technology, this can equate to subcentimeter resolution. External reference control (e.g., GPS) is required to georeference the location of the resultant model. However, photogrammetry can create accurately scaled models without an external reference. Occasionally, onboard external reference control is included with airborne photogrammetry data.

- b. **Applicability - High**  
Airborne photogrammetry can capture nearly every deposit that is visible from the air.
- c. **Level of Effort - Medium**  
Generally, a pilot is necessary to collect airborne photogrammetric data. Either contracted pilots or the NOC's UAS services can collect the imagery. UAS data collection may require several days of field work, depending on the size of the deposit(s). A minimum of 2 to 4 weeks of mission planning is also required to use a UAS. Contracted data collection missions can be flown in a matter of days if the effort meets certain contracting criteria. It is possible to successfully use kites and balloons at smaller sites.
- d. **Reliability - High**  
The surface models derived from airborne data collection methods are highly reliable.
- e. **Specialized Knowledge - High**  
Airborne data collection via fixed-wing aircraft requires a licensed and certified pilot, a plane, and special cameras and accessories. UAS data collection requires a pilot certified by the Department of the Interior to operate the UAS.
- f. **Cost - Low to Medium**  
The NOC maintains two UASs. The cost to use these services in 2016 is about \$4,000, most of which is travel costs for the aircraft and certified UAS

pilot. As of 2016, the NOC covers the base salary of NOC UAS pilots. UAS services can occasionally be contracted for \$3,500, depending on the size, location, and complexity of the project. A contracted fixed-wing data collection event generally costs about \$20,000. However, the fixed-wing data collection event can capture multiple deposits within a geographic area for minimal price increases, reducing the cost per site.

- g. **Overall - Average to Good**  
Airborne photogrammetry provides highly accurate, high-resolution models of the surfaces of deposits. If resources are available, this method produces reliable results. Cost and time sensitivity are the most prohibitive factors with this method.

### 3.1.4 Analog Measurements

Analog measurements involve the use of nondigital devices (e.g., tape measures, measuring wheels) to measure the dimensions of deposits.

- a. **Accuracy - Low**  
Errors in analog measurements can range from feet to meters. This inaccuracy can lead to severe over- or underestimation of the volume calculation of the deposit.
- b. **Applicability - High**  
Analog devices can measure virtually any deposit that is accessible.
- c. **Level of Effort - Low**  
Analog measurements do not require much time or resources, other than the potential need to traverse terrain in order to take the measurements.
- d. **Reliability - Low**  
Inaccurate measurements lead to over- or underestimates of volumes of deposit material.
- e. **Specialized Knowledge - Low**  
Using analog methods to measure

surfaces of deposits requires an understanding of geometry and how to collect proper measurements.

f. **Cost - Low**

Tape measures or measuring wheels cost less than \$100. Hand sights range from \$100 to \$500. Certified surveyors can make the measurements, though these generally require contracting or larger amounts of money.

g. **Overall - Poor**

Analog measurements are appropriate when rough estimates are sufficient or when other methods are unavailable. However, this method is beneficial during early site visits to approximate the scale of future data collection events.

## 3.2 Subsurface Plane Measurements

The subsurface plane of a deposit is the contact between the deposited material (e.g., mine waste) and a reference material (often undisturbed earth) (see Figure 3). For the purpose of this tech note, the data collection methods discussed in this section exclude the possibility of relocating the entire deposit and measuring the subsurface plane itself. The data collected using the methods in this section do not represent the entire subsurface plane of the deposit. These methods measure information about either points or linear transects along the subsurface plane, which are then extrapolated to create a plane. The subsurface plane derived using these methods does not represent the “true” subsurface plane of the deposit but a “best fit” subsurface plane due to the assumptions made when extrapolating points or lines of a plane. In this section, the data collection methods include intrusive and non-intrusive techniques, including drilling, trenching, geophysics, landscape interpolation by GPS, and aerial photography. The data collection method ratings range from very low to high regarding their performance at measuring the subsurface plane of deposits. However, the accuracy section analyzes how well the

data can be used to make the “best fit” subsurface plane. Methods also include overall ratings of poor, average, good, or very good.

### 3.2.1 Intrusive Methods

Intrusive data collection methods expose the contact between the deposit and the reference material (e.g., undisturbed earth). These methods are used to measure the distance of points and lines along the subsurface plane of the deposit. Intrusive methods typically involve the use of heavy machinery.

#### 3.2.1.1 Drilling

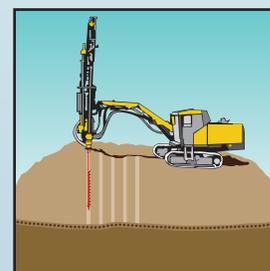
Drilling, also referred to as boring, involves excavating deposit material at point locations until the contact between the deposit and the reference material is exposed. Measurements are typically recorded as depth distance, or “beneath ground surface.” Machine operators use heavy machinery to complete most of the drilling. On occasion, hand augers substitute heavy machinery. Those conducting the drilling do not see the contact between the deposit and the reference material “in situ” (or at its actual location); drillers identify the contact through the material brought up by the drilling process.

a. **Accuracy - Varies**

Drilling exposes the contact between the deposit and the reference material, accurate to inches. The resulting accuracy of the subsurface plane depends on the density of drilled points.

b. **Applicability - Medium to High**

Drilling equipment bores a hole vertically through the deposit, therefore requiring the equipment to be on top of the deposit. The applicability of drilling decreases as the size and complexity of the deposit increases. However, drilling is applicable for the largest deposits with graded and stable surface access. Hand augers are well suited for small deposits or deposits with a fine material



consistency in which manual boring can be performed. The hand auger's applicability decreases as the deposit or deposit particle size increases.

**c. Level of Effort - High**

To perform drilling on BLM sites, requirements include contracting, staff oversight, and records management.

**d. Reliability - Medium to High**

The reliability of the subsurface plane created from drilling data ranges from medium to high, increasing with the density of point data. Though rare, the contact boundary can be incorrectly identified since the boundary is not visible from the surface.

**e. Specialized Knowledge - High**

Equipment operators and geologic technicians operate equipment and recognize when drilling operations reach the boundary between the deposit and reference material.

**f. Cost - Medium**

Due to the specialized knowledge and required equipment, contractors perform drilling work. Contract costs typically range from \$10,000 to \$30,000 but can be higher depending on site location and number of drilling locations.

**g. Overall - Good**

Though somewhat expensive, this method reliably creates a subsurface plane for calculating volumes.

### 3.2.1.2 Trenching

Trenching involves excavating material in a linear orientation across deposits, exposing the contact between the deposit and the reference material along a transect. Those conducting trenching identify the contact "in situ" and conduct measurements along the transect. Equipment operators perform trenching with heavy machinery.

**a. Accuracy - High**

Linear information about the contact between the deposit and the reference

material allows for highly accurate measurements of the subsurface plane. Increasing the number of transects across the pile increases the accuracy of the subsurface plane.

**b. Applicability - High**

Trenching is highly viable for small to medium deposits, as long as the deposit is accessible to equipment and as long as space is available to store excavated material. As the sizes of deposits increase, the applicability of trenching decreases, since operators must remove a greater volume of material to expose a linear transect along the subsurface plane.

**c. Level of Effort - High**

Trenching on BLM sites usually requires contracting, staff oversight, and records management. Mobilization and operation of equipment also requires a substantial amount of time. Additionally, the larger the pile, the greater the level of effort in order to expose a complete transect across the pile.

**d. Reliability - High**

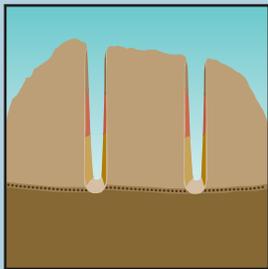
Trenching produces reliable information about linear transects of the subsurface plane. This information can be used to easily and reliably calculate a subsurface plane for volume calculation.

**e. Specialized Knowledge - Medium**

Trained equipment operators and geologic technicians operate equipment, recognize when trenching operations reach the boundary between the deposit and reference material, and are aware of the safety hazards associated with trenching.

**f. Cost - Medium to High**

Due to the high level of effort, operation time, and mobilization, trenching costs range from \$20,000 to \$50,000 or higher, depending on the size of the deposit and number of transects.



g. **Overall - Good**

Trenching produces the largest amount of reliable information of the subsurface plane without relocating the entire deposit and measuring the plane itself. Costs increase as deposit size increases. Only the largest deposits render this method ineffective.

### 3.2.2 Non-Intrusive Methods

Non-intrusive data collection methods do not disturb earth or expose the contact between the deposit and the reference material. Rather, these methods use information gathered about the surface or measurements of the subsurface to estimate where the subsurface plane exists.

#### 3.2.2.1 Geophysics

Geophysical methods (e.g., direct current resistivity, ground-penetrating radar) measure the physical properties of the subsurface. Measurements of both the deposit and reference material are usually collected in linear or 3D orientations from the surface at varying but defined depths. A geologist or geophysicist interprets the collected data to identify the contact between the deposit and reference material.

a. **Accuracy - Medium**

Depending on the geophysical method and the amount of spacing between data collection lines or electrodes, accuracy ranges from inches to several feet. The subsurface plane calculated from these data is fairly accurate within this range since it is based on linear survey lines and not points.

b. **Applicability - Medium**

Some site-specific conditions (e.g., electrically conductive sites, sites in which the physicochemical differences between the deposit and the reference material are minimal) interfere with or inhibit certain geophysical methods and decrease applicability. Otherwise, geophysical methods can be performed at any site where access is permitted.

c. **Level of Effort - Medium**

Most data collection events take no more than 2 days. For larger sites, data collection takes days to weeks. In addition, a geophysical survey requires time for contracting procedures.

d. **Reliability - Medium**

A trained individual measures the geophysical properties of the subsurface and interprets the data. When correctly interpreted, the subsurface plane allows for reliable volume calculation.

e. **Specialized Knowledge - High**

Using geophysical methods to measure the subsurface plane of deposits requires specialized knowledge about which geophysical method to use, how to operate the equipment, and how to correctly interpret the data.

f. **Cost - Low to Medium**

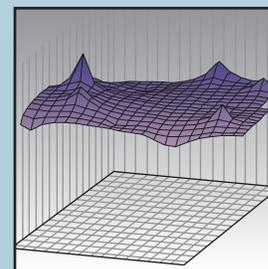
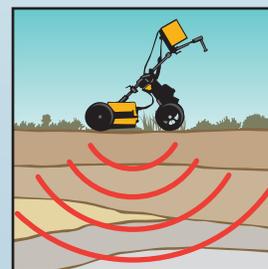
The initial purchase cost of geophysical equipment is high (between \$50,000 and \$100,000). However, the NOC maintains some equipment. If the NOC's services are used, travel and labor hours are the only associated cost (estimate of \$3,500) with geophysical data collection. Costs for geophysical data collection are higher when contracted (\$20,000-\$30,000 per site).

g. **Overall - Average**

Based on the specialized knowledge requirement and the uncertainty involved with interpretation, geophysics is an adequate solution for calculating the area of a subsurface plane.

#### 3.2.2.2 Landscape Interpolation

GPS can be used to measure information about an area surrounding a deposit. These data points are then uploaded into a geographic information system and used to interpolate the subsurface plane of the area underneath the deposit. GPS measurements generally start at the outermost extent of the deposit and radiate outward. Landscape interpolation should always be performed with the best available GPS data collection





technique (i.e., differentially corrected GPS data).

a. **Accuracy - Low**

Although GPS is capable of achieving subcentimeter accuracy, the information about the subsurface plane is low due to interpolation. Additional information, such as drilling or hand-augured data, to validate the plane increases the accuracy. The accuracy of this method is better for less complex or flatter landscapes.

b. **Applicability - High**

This method can be performed at any site in which access to the deposit is permitted.

c. **Level of Effort - Low**

This method only requires the collection of points at and surrounding the edge of the deposit. The level of effort increases with difficult terrain, larger deposit sizes, and higher point density.

d. **Reliability - Low**

The elevation of the subsurface of the interpolated plane can vary widely. In some cases, areas of the interpolated plane, based on the interpolation technique, can be calculated to exist above the surface (measured) plane; thus, the volume of the area where the subsurface plane was calculated to exist above the measured plane would be negative, essentially invalidating this method. Less complex or flatter landscapes produce a more reliable subsurface plane, as do interpolated surfaces informed with drilling or hand-augured data.

e. **Specialized Knowledge - Medium**

Setup, operation, and data transfer for differential GPS requires some training. Individuals require the ability to troubleshoot communication issues between the base and the rover in the field and knowledge of vendor-specific software protocols. Individuals also require training in spatial analysis and interpolation techniques in order

to successfully perform landscape interpolation.

f. **Cost - Low to Medium**

Most of the costs associated with landscape interpolation are related to data collection (estimate of \$3,500). If differential GPS is used, costs are incurred from acquiring equipment or services and performing the interpolation (estimate of \$10,000). Most interpolation can be performed using GIS software (e.g., ArcGIS), which can be obtained through an annual software license for approximately \$1,000.

g. **Overall - Poor**

The quality of the subsurface plane based on GPS data is highly variable. This technique should only be used when the landscape surrounding the deposit is very simple or flat.

### 3.2.2.3 Aerial Photography

If aerial photography was captured prior to mining disturbance and is available in stereo, very accurate models of the subsurface plane can be calculated using photogrammetry. This method is very accurate, assuming undisturbed earth is the reference medium upon which the deposit sits. This method requires georeferencing the surface plane so it correlates to the aerial photography. Overburden (e.g., soil) can be factored into volume calculations if the surface is undisturbed.

a. **Accuracy - Medium to High**

The accuracy of the subsurface plane ranges from inches up to a foot and is based on the scale of the photography.

b. **Applicability - Low**

Many sites predate aerial photography or do not indicate premine site conditions. Additionally, the scale of the photography and its subsequent effects on the resolution of the model should be evaluated against project objectives. Based on the lack of availability, the applicability of this method is low.

c. **Level of Effort - Low**

Efforts include staff time to research the availability of the photography and, if available, to calculate the subsurface plane.

d. **Reliability - High**

If available, aerial photographs are very reliable for calculating the area of a subsurface plane.

e. **Specialized Knowledge - Medium**

Individuals require knowledge about photogrammetry and digitization and the ability to calculate a subsurface plane based on aerial photography.

f. **Cost - Low**

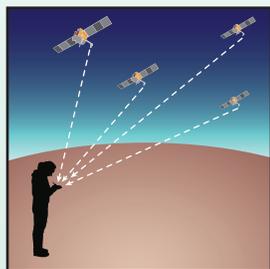
Staff time is the main cost associated with this data collection method. Also, sometimes aerial photography is available from private companies at a minimal cost. This cost ranges from \$0 if available within the BLM to \$1,000 if purchased.

g. **Overall - Very Good**

This method is a very inexpensive yet reliable method of calculating a subsurface plane if the imagery is available.

## 4. Data Collection Methods for Pits |

For active mining monitoring compliance, the volume of material (e.g., sand, gravel, stone) is calculated. The exposed faces of pits (the subsurface planes) can be accurately measured through several methods. The surface planes of pits are typically estimated unless other data are available (e.g., aerial photography, preexisting data). Further, pit volume calculations can be used for Abandoned Mine Lands Program operations. For example, pit volume calculations can facilitate high well reduction for physical safety hazard mitigation.



### 4.1 Subsurface Plane Measurements

The exposed faces, or subsurface planes, of pits can be accurately measured. In this tech note, the data collection methods for measuring the subsurface planes of pits and the surface planes of deposits are identical; however, some methods are better suited for measuring the subsurface planes of pits than the surface planes of deposits. This section presents these data collection methods and provides qualitative ratings from very low to high regarding their performance at measuring the subsurface planes of pits. In addition to the criteria used to rate the data collection methods for the surface planes of deposits, defensibility is added due to the legal implications of production verification at active mining operations. Overall ratings of data collection methods for pits include poor, average, good, or very good.

#### 4.1.1 Global Positioning System

GPS provides location information based on transmissions from a network of satellites orbiting the earth. GPS measures the surface of a deposit in two ways. First, a grid of user-defined resolution delineates point locations on the surface of the pit. This information is then interpolated into a smooth surface containing the horizontal (X, Y) attribute

information with the vertical (Z) elevation values. The second way is to collect continuous linear transects over the pit. The X, Y, and Z values of the exposed surface are interpolated from the lines. The two types of GPS include standalone and differential.

##### 4.1.1.1 Standalone GPS

A standalone system involves the use of a handheld unit that processes signals from at least four satellites to calculate location information.

###### a. Accuracy - Low to High

The accuracy of the resultant model relies on the accuracy and resolution of the collected data. Standalone systems provide accuracy within a range of  $\pm 2$  to 5 meters. The use of an external antenna can improve the accuracy by  $\pm 1$  to 2 meters. Generally, this amount of accuracy is not sufficient to calculate volumes for small to medium deposits.

###### b. Applicability - Medium

The main constraint with using GPS is those collecting the data must traverse the exposed surface of the pit. Safety concerns regarding slips, trips, and falls or the large dimensions of pits often outweigh the benefit of using GPS to collect information. Additionally, the applicability of standalone GPS is limited to very large pits in which the level of accuracy is insignificant compared to the size of the pit.

###### c. Level of Effort - Medium

The required level of effort for collecting GPS data depends on the size of the pit and the desired resolution of the surface plane model. As the pit size and desired resolution increases, the amount of time and effort increases.

###### d. Reliability - Very Low to Medium

The reliability of standalone GPS is very low to medium, depending on the size of the pit. Standalone GPS reliability increases when the pit is

so large that an accuracy range of  $\pm 2$  to 5 meters is insignificant compared to the overall size of the target object. The reliability is very low for smaller pits because an accuracy range of  $\pm 2$  to 5 meters significantly affects the confidence and accuracy of the resultant model and volume estimate.

e. **Specialized Knowledge - Low**

Many individuals are familiar with the operation of standalone GPS units for data collection. Individuals should be properly trained in configuring GPS devices prior to collecting data.

f. **Cost - Low**

Generally, standalone GPS units are inexpensive, often between \$400 and \$3,000. However, accuracy and desired model resolution should factor into which GPS device to use.

g. **Overall - Average**

GPS can serve as a data collection method for measuring points along the exposed face of pits. However, based on the size and complexity of most pits, GPS can be a very time-consuming method. If time is available, GPS can produce a very accurate plane for volume calculations.

h. **Defensible - No**

Typically, GPS points alone are insufficient to serve as defensible data.

#### 4.1.1.2 Differential GPS

A differential GPS system involves the use of a stationary base station and rover combination, which provides much higher positional accuracy than standalone GPS. Data collected in the field are processed and corrected afterward using information published by the Online Positioning User Service to improve the accuracy. Differential GPS can be performed in the field and corrected nearly instantaneously using radios known as “real time kinematic” (RTK).

a. **Accuracy - High**

The accuracy of the resultant subsurface plane relies on the accuracy and resolution of the collected data. Differential GPS systems can achieve subcentimeter accuracy. This can result in a very accurate subsurface measurement and is often more than enough information to calculate a reliable model for pits. Higher density grids (increased number of total points on the exposed face) or shorter distances between linear transects result in a higher resolution model with greater accuracy.

b. **Applicability - Medium**

The main constraint with using GPS to collect data is that those collecting the data must traverse the exposed face of the pit. Safety concerns regarding slips, trips, and falls or the large dimensions of pits often outweigh the benefit of using GPS. Differential GPS is applicable for all sizes of pits that do not pose safety hazards and in which pit dimensions do not interfere with data collection.

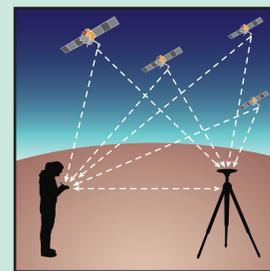
c. **Level of Effort - Medium**

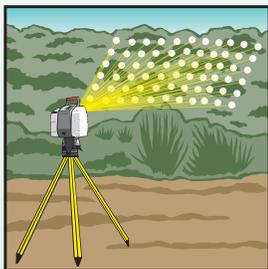
The required level of effort for collecting GPS data depends on the size of the pit and the desired resolution. Since GPS data is collected from the location of the rover, the pit must be traversed. The larger the pit, the more time and exertion required to collect information. Also, the higher the desired resolution, the more time required for collecting data. Differential GPS systems also have an additional time requirement associated with setting up and taking down a base station.

d. **Reliability - Medium to High**

The resolution of collected data points determines whether the reliability is medium or high. The higher the resolution, the higher the reliability.

e. **Specialized Knowledge - Medium**  
Setup, operation, and data transfer





for differential GPS requires some training. Individuals require the ability to troubleshoot communication issues between the base and the rover in the field and knowledge of vendor-specific software protocols.

f. **Cost - Low to Medium**

RTK differential GPS systems cost between approximately \$10,000 and \$30,000. Instead of purchasing an RTK system, users can also rent one. Startup costs for non-RTK differential GPS systems are lower but typically require yearly software fees for incorporating data processed by the Online Positioning User Service. There is a very low annual equipment maintenance cost, often \$0, associated with RTK differential GPS systems. For BLM staff, the NOC maintains two RTK differential GPS systems. The NOC can train individuals on the operation of the units or perform the data collection if necessary. Travel ceiling implications apply when considering hands-on training or NOC data collection. However, shipping costs for the equipment are minimal. The largest cost associated with data collection via RTK differential GPS is typically travel costs (transportation, per diem).

g. **Overall - Good**

Although this method produces highly accurate and reliable results, it should only be used if the proper expertise is available and defensible data are not needed.

h. **Defensible - No**

Typically, GPS points alone are insufficient to serve as defensible data.

### 4.1.2 Laser Scanning

Laser scanning, also referred to as light detection and ranging (LiDAR), operates on the principle of measuring the amount of time it takes a pulse of light to reflect off an object and back to the scanner. This provides a measurement of the distance between

the scanner and object, which can create scaled 3D models of any object off of which the light reflects. The datasets are generally referred to as point clouds, with each measurement representing a point in space. LiDAR captures datasets from the ground (terrestrial laser scanning) or from the air (airborne laser scanning).

#### 4.1.2.1 Terrestrial Laser Scanning

In terrestrial laser scanning, a laser scanner collects data from a stationary location on the ground. Sometimes, to capture an entire pit with terrestrial laser scanning, multiple data locations are necessary.

a. **Accuracy - High**

Laser scanners can accurately measure the shape and size of pits to decimeter resolution. External reference control (e.g., GPS) is required to georeference the location of the resultant model. However, laser scanners can create accurately scaled models without external reference.

b. **Applicability - High**

Laser scanners collect information from a stationary location. An individual can scan most pits from as little as two locations. An individual can scan small pits from one location, assuming all edges of the pit can be seen from that location.

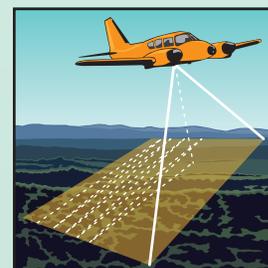
c. **Level of Effort - Low**

The level of effort is low for most pits, which require scanning from only one or two locations. Larger, more complex pits require additional data collection locations to adequately capture the surface.

d. **Reliability - High**

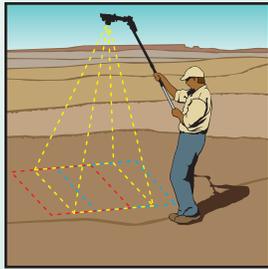
The subsurface plane created using laser scanning is highly reliable. The data collected by the laser scanner typically has a low amount of error and is accurate and precise. Reliability increases when the resolution and number of data collection locations increase.

- e. **Specialized Knowledge - Medium**  
Most individuals require training in the operation of LiDAR equipment and data processing. However, advances in the LiDAR field have resulted in “user friendly” LiDAR instrumentation and data processing software packages. Once trained, data collection and processing require little additional specialized knowledge.
- f. **Cost - Medium to High**  
Laser scanner costs range from approximately \$40,000 to \$60,000, depending on the model. This does not include training costs. Annual maintenance costs are very low, often \$0.
- g. **Overall - Good**  
Though startup costs for laser scanning are high, the low maintenance and ease of use make it one of the industry standard methods in measuring the exposed faces of pits.
- h. **Defensible - Yes**  
The models created using laser scanning data can be reproduced, and when tied to locations with external references or ground control (e.g., GPS), the models have a high defensibility.
- 4.1.2.2 Airborne Laser Scanning**  
Airborne laser scanning uses laser scanners that are mounted on manned or unmanned aircraft. The laser scanners collect data when the aircraft flies over individual site locations. Unlike terrestrial laser scanning, the sensor is constantly in motion, which prevents the user from having to physically move the laser scanner to multiple locations around the pit.
- a. **Accuracy - High**  
Laser scanners can accurately measure the shape and size of pits to decimeter resolution. External reference control (e.g., GPS) is required to georeference the location of the resultant model. However, laser scanners can create accurately scaled models without external reference.
- b. **Applicability - High**  
Laser scanners affixed to an aircraft can capture nearly every pit that is visible from the air.
- c. **Level of Effort - Medium**  
Airborne laser scanning is rated medium due to the contracting or coordination requirements for obtaining flight clearances and aircraft. The NOC currently does not maintain a UAS-ready laser scanner, so contracting is necessary.
- d. **Reliability - High**  
The subsurface plane created using laser scanning is highly reliable. The data collected by the laser scanner typically has a low amount of error and is accurate and precise.
- e. **Specialized Knowledge - High**  
Airborne data collection via aircraft requires a licensed and certified pilot, a plane, and special equipment. UAS data collection requires a pilot certified by the Department of the Interior to operate the UAS.
- f. **Cost - Medium**  
An airborne data collection event can cost between \$30,000 and \$35,000. This amount is cost prohibitive if only one pit is captured. However, if multiple sites lie within a defined geographic radius, the cost per site decreases.
- g. **Overall - Good**  
Though the cost of the data collection mission can be relatively high, incorporating multiple sites into a single mission can reduce the cost per site. LiDAR datasets are defensible, accurate, and highly reliable.
- h. **Defensible - Yes**  
The models created using laser scanning data can be reproduced, and when tied to locations with external references or ground control (e.g., GPS), the models have a high defensibility.



### 4.1.3 Photogrammetry

Photogrammetry calculates a 3D model of surfaces using adjacent, overlapping photographs. This data collection method results in very accurate 3D models by using effectively captured photographs of an object. The two methods of collecting photogrammetric images include ground based and airborne.



#### 4.1.3.1 Ground-Based Photogrammetry

Ground-based photogrammetry involves capturing photographs from either the photographer's eye level or from an object extended up from ground level (e.g., monopod, cherry picker).

##### a. Accuracy - High

Photogrammetry can produce models that accurately represent the shape and size of pits. With current photographic technology, this can equate to subcentimeter resolution. External reference control (e.g., GPS) is required to georeference the location of the resultant model. However, photogrammetry can create accurately scaled models without an external reference.

##### b. Applicability - Medium

In order to create an accurate model, the photographer must capture the entire exposed face, including the pit floor, in overlapping photographs. This requires the photographer to move the camera around the pit to adequately capture the exposed face. The greater the complexity of the topographic features or the greater the size of the pit, the more difficult and less applicable this method becomes. This is due to the limitations of the photographer in reaching the necessary vantage points to adequately capture the pit stereoscopically, or in stereo.

##### c. Level of Effort - Low to High

Photographers can capture small or simple pits stereoscopically in less than an hour. Larger pits or more complex topographic features on the

exposed surface of pits can prove challenging and time consuming, often requiring multiple days to capture stereoscopically.

##### d. Reliability - Medium

Assuming the photographer collected effective photographs, models derived from ground-based photogrammetry are reliable. The models fail when effective photographs of the pit have not been captured, which occasionally occurs when collected from the ground.

##### e. Specialized Knowledge - Medium

If not already known, initial training of how to capture objects in stereo is required. For complex pits, a higher level of understanding of photogrammetric principles is recommended, but not always necessary, for successful 3D models.

##### f. Cost - Low

A fixed-aperture DSLR camera, approximately \$300, is the minimum recommended technology for capturing effective photographs. Higher megapixel, fully programmable DSLR cameras (which range from \$800 to \$6,000) are more reliable. Camera and travel costs are the only required costs, besides labor hours for photogrammetric data collection.

##### g. Overall - Average

Ground-based photogrammetry is a good method for collecting data about small pits. Its overall rating decreases substantially for larger or more complex pits due to the increased level of effort and higher chance that the models will fail.

##### h. Defensible - Yes

Successful models created using ground-based photogrammetry data can be reproduced, and when tied to locations with external references or ground control (e.g., GPS), the models have a high defensibility.

#### 4.1.3.2 Airborne Photogrammetry

Airborne photogrammetric data collection involves fixing a camera to an aircraft and collecting stereoscopic photographs from the air. These aircraft can include a fixed-wing or rotary-wing passenger aircraft or a UAS. The airborne aspect of this method eliminates vantage point issues associated with ground-based photogrammetry.

##### a. Accuracy - High

Photogrammetry can produce models that accurately represent the shape and size of pits. With current photographic technology, this can equate to subcentimeter resolution. External reference control (e.g., GPS) is required to georeference the location of the resultant model. However, photogrammetry can create accurately scaled models without an external reference. Occasionally, onboard external reference control is included with airborne photogrammetry data.

##### b. Applicability - High

Airborne photogrammetry can capture nearly every pit that is visible from the air.

##### c. Level of Effort - Low to Medium

Generally, a pilot is necessary to collect airborne photogrammetric data. Either contracted pilots or the NOC's UAS services can collect the imagery. UAS data collection may require several days of field work, depending on the size of the pit(s). A minimum of 2 to 4 weeks of mission planning is also required to use a UAS. Contracted data collection missions can be flown in a matter of days if the effort meets certain contracting criteria. It is possible to successfully use kites and balloons at smaller sites.

##### d. Reliability - High

The models derived from airborne data collection methods are highly reliable.

##### e. Specialized Knowledge - High

Airborne data collection via fixed-wing aircraft requires a licensed and certified

pilot, a plane, and special cameras and accessories. UAS data collection requires a pilot certified by the Department of the Interior to operate the UAS.

##### f. Cost - Low to Medium

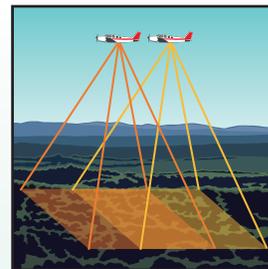
The NOC maintains two UASs. The cost to use these services in 2016 is about \$4,000, most of which is travel costs for the aircraft and certified UAS pilot. As of 2016, the NOC covers the base salary of NOC UAS pilots. UAS services can occasionally be contracted for \$3,500, depending on the size, location, and complexity of the project. A contracted fixed-wing data collection event generally costs about \$20,000. However, the fixed-wing data collection event can capture multiple pits within a geographic area for minimal price increases, reducing the cost per site.

##### g. Overall - Very Good

Airborne photogrammetry provides highly accurate, high-resolution models of the exposed faces of pits. If resources are available, this method produces reliable results. Cost and time sensitivity are the most prohibitive factors with this method.

##### h. Defensible - Yes

The models created using airborne photogrammetry data can be reproduced, and when tied to locations with external references or ground control (e.g., GPS), the models have a high defensibility

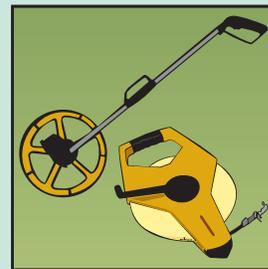


#### 4.1.4 Analog Measurements

Analog measurements involve the use of nondigital devices (e.g., tape measures, measuring wheels) to measure the dimensions of pits.

##### a. Accuracy - Low

Errors in analog measurements can range from feet to meters. This inaccuracy can lead to severe over- or underestimation of the volume calculation of the pit.





- b. **Applicability - High**  
Analog devices can measure virtually any pit face that is accessible.
- c. **Level of Effort - Low**  
Analog measurements do not require much time or resources, other than the potential need to traverse terrain in order to take the measurements. Analog measurements of very large pits can take days depending on the tool used.
- d. **Reliability - Low**  
Inaccurate measurements lead to over- or underestimates of volumes of material removed from pits.
- e. **Specialized Knowledge - Low**  
Using analog methods to measure the faces of pits requires an understanding of geometry and how to collect proper measurements.
- f. **Cost - Low**  
Tape measures or measuring wheels cost less than \$100. Hand sights range from \$100 to \$500. Certified surveyors can make the measurements, though these generally require contracting or larger amounts of money.
- g. **Overall - Poor**  
Analog measurements are appropriate when rough estimates are sufficient or when other methods are unavailable. However, this method is beneficial during early site visits to approximate the scale of future data collection events.
- h. **Defensible - No**  
Unless certified surveyors perform the measurements, the plane calculated from field measurements is generally not defensible.

## 4.2 Surface Plane Measurements

The surface plane of a pit is usually the undisturbed surface prior to mining

activity and may or may not include soil (overburden). Limited methods are available to re-create the initial (undisturbed) surface plane model. However, in most compliance monitoring cases where several data collection events occur for the same pit, the measurements of the subsurface plane from one mission may be used as the measurements of the surface plane in the next mission. In this section, the data collection methods for the surface planes of pits include preexisting data, aerial photography, “flat cap,” and landscape interpolation. If possible, an original ground survey should be conducted prior to permitting a new pit area in order to provide this information for later volume calculations.

### 4.2.1 Preexisting Data

Data used to create the subsurface plane of a pit in one data collection effort may be used to represent the surface plane in a future data collection effort. Preexisting data is typically the most reliable source of data for calculating changes in material removed from pits between points in time. This is discussed further in section 7, “Active Mine Monitoring Application.”

### 4.2.2 Aerial Photography

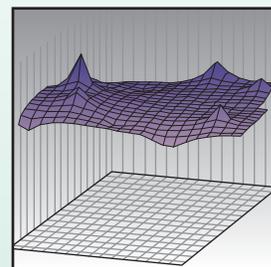
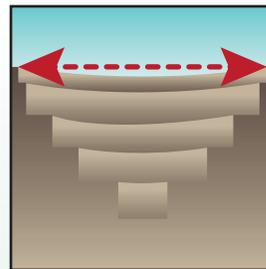
If aerial photography predates mining operations and is available in stereo, a reliable surface plane can be calculated using photogrammetry. However, the resulting volume calculation has the potential to include overburden material (i.e., the material—usually natural rock and soil—that overlays the material that will be mined). If the photography was captured at a point in time when the overburden had been removed, then overburden will not be included in the volume calculation. If the target mine material had not yet been mined, then overburden may be included in the volume calculation; this is acceptable for scenarios in which the total undisturbed volume is desired. Otherwise, an estimate of the volume of the overburden must be subtracted from the volume of the final mined material.

### 4.2.3 “Flat Cap”

This method is used to create the initial surface when preexisting surface data is unavailable. The flat cap method assumes that the most elevated points of the pits represent the widest extent of the surface plane. A minimum bounding surface is created between these points. The surface developed from this approach results in a conservative minimum volume estimate.

### 4.2.4 Landscape Interpolation

Landscape interpolation uses topographic information surrounding pits to develop a best fit model that represents the natural shape of the surface prior to excavation. This method generally is very time consuming and often results in an unrealistic surface plane.



## 5. Data Collection Method Comparisons |

The previous sections present the data collection methods as individual components. Tables 2 and 3 provide a

comparative overview of the data collection methods for the surface and subsurface planes of deposits and pits.

**Table 2.** Comparative overview of the surface and subsurface plane data collection methods for deposits

Surface Plane Data Collection Methods	Accuracy	Applicability	Level of Effort	Reliability	Specialized Knowledge	Cost (Rating)	Cost (\$)	Overall
Standalone GPS	Low	Low	Medium	Very Low to Medium	Low	Low	\$400 - \$3,000	Average
Differential GPS	High	Medium	Medium	Medium to High	Medium	Medium	\$10,000 - \$30,000	Good
Terrestrial Laser Scanning	High	Medium to High	Low to Medium	High	Medium	Medium to High	\$40,000 - \$60,000	Good
Airborne Laser Scanning	High	High	Medium	High	High	Medium	\$30,000 - \$35,000	Average to Good
Ground-Based Photogrammetry	High	Medium	Low to High	High	Medium	Low	\$300 - \$6,000	Poor to Good
Airborne Photogrammetry	High	High	Medium	High	High	Low to Medium	\$3,500 - \$20,000	Average to Good
Analog Measurements	Low	High	Low	Low	Low	Low	\$100 - \$500	Poor
Subsurface Plane Data Collection Methods	Accuracy	Applicability	Level of Effort	Reliability	Specialized Knowledge	Cost (Rating)	Cost (\$)	Overall
Drilling	Varies	Medium to High	High	Medium to High	High	Medium	\$10,000 - \$30,000	Good
Trenching	High	High	High	High	Medium	Medium to High	\$20,000 - \$50,000	Good
Geophysics	Medium	Medium	Medium	Medium	High	Low to Medium	\$3,500 - \$30,000	Average
Landscape Interpolation	Low	High	Low	Low	Medium	Low to Medium	\$3,500	Poor
Aerial Photography	Medium to High	Low	Low	High	Medium	Low	\$0 - \$1,000	Very Good

**Table 3.** Comparative overview of the subsurface and surface plane data collection methods for pits

<b>Subsurface Plane Data Collection Methods</b>	<b>Accuracy</b>	<b>Applicability</b>	<b>Level of Effort</b>	<b>Reliability</b>	<b>Specialized Knowledge</b>	<b>Cost (Rating)</b>	<b>Cost (\$)</b>	<b>Overall</b>	<b>Defensible</b>
Standalone GPS	Low to High	Medium	Medium	Very Low to Medium	Low	Low	\$400 - \$3,000	Average	No
Differential GPS	High	Medium	Medium	Medium to High	Medium	Low to Medium	\$10,000 - \$30,000	Good	No
Terrestrial Laser Scanning	High	High	Low	High	Medium	Medium to High	\$40,000 - \$60,000	Good	Yes
Airborne Laser Scanning	High	High	Medium	High	High	Medium	\$30,000 - \$35,000	Good	Yes
Ground-Based Photogrammetry	High	Medium	Low to High	Medium	Medium	Low	\$300 - \$6,000	Average	Yes
Airborne Photogrammetry	High	High	Low to Medium	High	High	Low to Medium	\$3,500 - \$20,000	Very Good	Yes
Analog Measurements	Low	High	Low	Low	Low	Low	\$100 - \$500	Poor	No
<b>Surface Plane Data Collection Methods</b>								<b>Overall</b>	
Preexisting Data*								Very Good	
Aerial Photography								Good	
Flat Cap								Average	
Landscape Interpolation								Poor	

\*This method is only an option where data collection has occurred for the same pit in the past. For the first or a one-time data collection event, one of the other methods must be used.

## 6. Data Analysis Phase |

After information on both the surface and subsurface planes have been collected, the data are processed into planes during the data analysis phase, the second phase for calculating volumes. These planes are compared against each other to calculate volumes. This section discusses, in general, how data are prepared for analysis and the methods used to calculate volumes.

### 6.1 Data Preparation

After collecting the data regarding target objects, some processing is required to generate the planes for volume calculation. For most analytical methods, both surface and subsurface planes are required to calculate volumes. The data collection methods presented in this document typically record the location of data points from a surface or the locations of lines of data along a surface. Through interpolation, planes can be created from these datasets. This step is often accomplished through contouring and surface modeling software packages including Golden's Surfer or Esri's ArcMap.

Prior to analysis, the surface and subsurface planes are aligned where X and Y directions correspond to locations in a coordinate system. Global (latitude/longitude) or local (user-defined) coordinate systems can be used. Z values of the planes must represent height above a global or local (user-defined) datum. After aligning the two planes, volumes can be calculated.

### 6.2 Data Analysis Methods

After the surface and subsurface planes have been created, volume calculations can be derived. The three general methods of calculating volumes<sup>3</sup> include:

<sup>3</sup> These methods calculate bank volumes. Factors for bulking or compaction need to be discussed with engineers and incorporated into the final volume calculation.

#### 6.2.1 Digital Terrain Model Software

Software suites, such as ArcMap or AutoCAD Civil 3D, calculate volumes by comparing the differences between two surfaces. "Cut and fill" or surface subtraction types of analysis calculate distance differentials between the two surfaces at all regular, defined locations known as subareas or cells. Each differential is multiplied by the cell's area to identify a partial volume. The partial volumes are added to calculate total volume (or total volume of material removed).

#### 6.2.2 Average End Area

The "average end area" method requires a topographic drawing, either surveyed or calculated from the surface of a deposit or the subsurface of a pit, and a way to compute areas, such as an engineer scale or software, to determine the area of the target object at each contour. The area of each contour is determined and multiplied by the elevation difference between each contour. After each contour level area is multiplied by the heights, all calculations are added to determine the volume.

#### 6.2.3 Geometric Calculations (Paper/Pencil)

This method relies upon analog measurements when no other method is available. The shape of the target object is approximated or separated in a piecewise fashion to known geometries (e.g., cones, hemispheres) for which volumes are calculated using standard formulas. If precise measurements are known, they can be used in GIS or CAD software to create a 3D polygon for which volumes can be calculated.

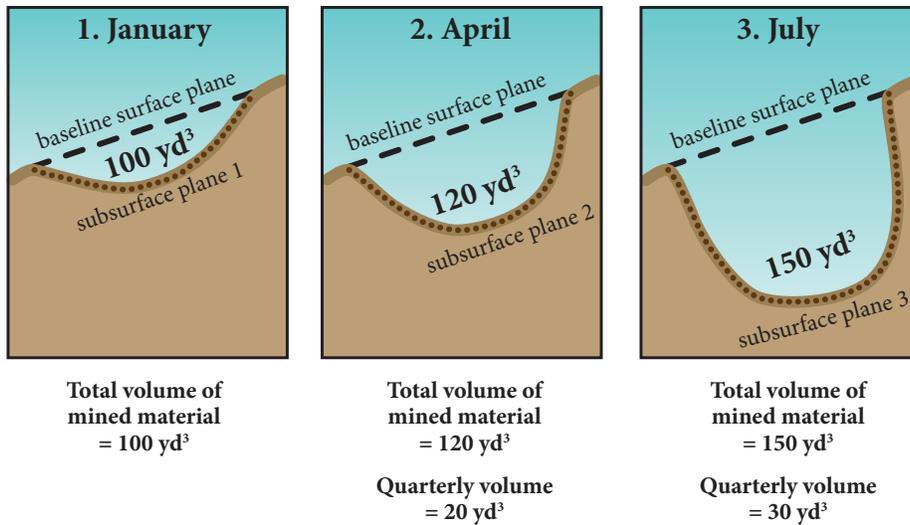
# 7. Active Mine Monitoring Application |

Active mines require regular monitoring for compliance, which often results in multiple data collection events. Two approaches are used regularly to calculate the volume of mined material. In one approach (Figure 5), a standard baseline surface plane (e.g., undisturbed earth) is used to calculate the amount of material removed for each data collection event. The subsurface plane is measured after each data collection event. After each data collection event, the volume of mined material is calculated using the standard baseline surface plane and the newly measured subsurface plane. The volume from one data collection event is subtracted from the volume of the previous

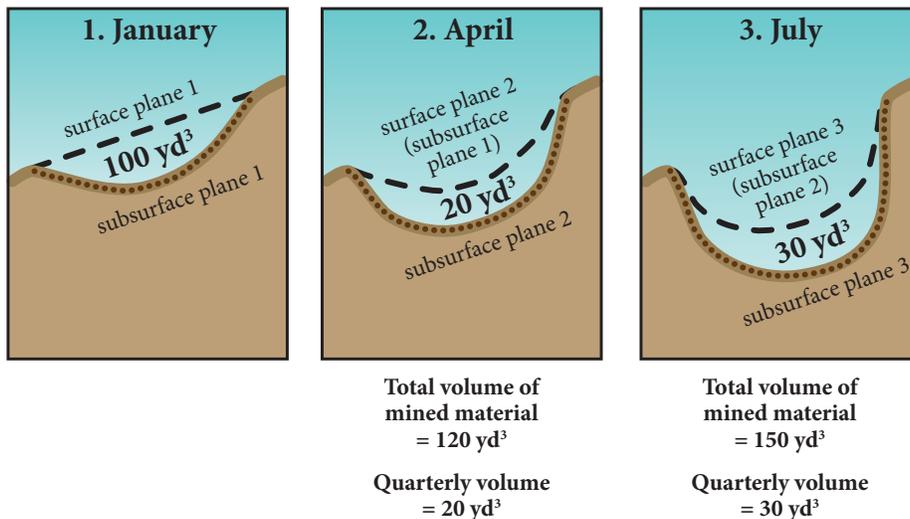
data collection event to calculate the amount of mined material for each quarter.

For the second approach (Figure 6), instead of using a baseline surface plane, the volume of mined material is calculated by using the subsurface plane from data collection event 1 as the surface plane for data collection event 2; the subsurface plane from data collection event 2 as the surface plane for data collection event 3; and so on. In either approach, data must be maintained from one data collection event to the next. If a baseline surface plane is not available, it is not possible to calculate the running total volume with this approach.

### Data collection events



### Data collection events



**Figure 5.** In this approach, the same baseline surface plane is used in each data collection event, and the new subsurface plane is measured each time.

**Figure 6.** In this approach, the subsurface plane for the previous data collection event becomes the surface plane for the next data collection event. The new subsurface plane is also measured each time.

## 8. Glossary |

**geometric object concept:** the indirect calculation of a real world object's volume through construction and analysis of a three-dimensional geometric object representing that real world object (e.g., tailings deposit). The geometric object is created through planes of analysis or surfaces that are measured (or estimated) of the real world object.

**surface plane:** one of the measurements required to calculate the volume of material remaining at a deposit or material removed from a pit. The surface plane data source varies depending on which target object is being analyzed. For deposits, the surface plane is the exposed face or measured face. For pits, the surface plane is the estimated plane or exposed face prior to excavation or disturbance.

**subsurface plane:** one of the measurements required to calculate the volume of material remaining at a deposit or material removed from a pit. The subsurface plane data source varies depending on which target object is being analyzed. For deposits, the subsurface plane is the estimated plane or the contact between the deposit and a reference medium (e.g., ground level or undisturbed earth). For pits, the subsurface plane is the bottom or exposed face of the pit that can be accurately measured.

**measured plane:** the exposed surface of a deposit or the bottom of a pit that can be directly measured.

**estimated plane:** either (a) the buried contact between a deposit and the earth or (b) the preexisting surface that was removed in open pit mining. Since these planes, or contacts, cannot be directly measured due to access or disturbances associated with mining, they are estimated.

**pit:** opening of the earth's surface used for the purpose of extracting rock, ore, or minerals.

**deposit:** processed or unprocessed earth material, including overburden (soil), waste rock, fill materials, and tailings, that has been removed from the subsurface and placed on the ground at a mine. In this publication, deposit does not refer to geologically emplaced deposits.

**tailings:** processed or unprocessed rock or ore deposits that are economically viable based on the precious minerals or other resources they contain.

**waste rock dump:** deposit of earth material that is removed during mining to reach ore or mineral bodies. Waste rock dumps are typically unprocessed. Also referred to as overburden.

**Global Positioning System:** a network of satellites that are used to determine the location (e.g., latitude, longitude) of an object on the earth's surface by transmitting radio waves between the satellites in orbit and a receiver on the earth's surface. Common receivers and manufacturers include Trimble (Juno, GeoXT) and Leica. Most smartphones are embedded with a GPS receiver.

**differential GPS:** a GPS data collection method used to improve the accuracy and precision of GPS units. In some cases, differential GPS can achieve subcentimeter accuracy. The collection of data is achieved by the processing of certain phases of GPS signals by both a base station (at a fixed location) and a rover. In real time kinematic differential GPS, a radio attaches to the base station that broadcasts the location information of the base to the rover, which can process the information instantaneously and improve location quality.

**georeferencing:** the process by which an image or digital map is assigned location parameters in space, usually in a computer-based system, such as a geographic information system. For example, a scanned topographic map, after georeferencing,

aligns properly in a coordinate system (e.g., Universal Transverse Mercator, or UTM) so that elevation information for a particular point on that map can be extracted.

### Deposit Sizes

**small:** between 1,000 and 20,000 cubic yards. Small deposits are typically reasonably navigable in at least two dimensions (e.g., width, length, or height) and can be traversed. Deposits at a typical low-production abandoned mine are generally on the higher end of small deposits.

**medium:** between 20,000 and 200,000 cubic yards. For this tech note, medium-sized deposits can be qualitatively described as those deposits that are larger than the small deposits but smaller than the large deposits (i.e., deposits unable to be traversed by foot). Usually, deposits of a medium size can only be easily measured from the ground in two dimensions.

**large:** greater than 200,000 cubic yards. These deposits can be larger than office buildings. Large (or very large) deposits can be hundreds of yards long in a single direction and typically are measured using remote platforms.

**Pit Sizes** (Geometric objects representing pits are typically much larger than those representing deposits.)

**small:** small pits have dimensions up to 800 meters across and no more than 100 meters deep. Small pits can stand alone or be part of larger pit mining operations.

**medium:** medium pits have dimensions up to about 1.5 kilometers across and 100-250 meters deep.

**large:** large pits are massive disturbances and can have dimensions of several kilometers across and up to a kilometer deep.

**photogrammetry:** the science of making measurements from photographs. Photogrammetry can produce three-dimensional surface models using overlapping, adjacent photographs.

**geophysics:** the study and analysis of the physical properties of the earth's subsurface in order to characterize and interpret natural or unnatural structures of the earth's subsurface. Structures may include faults, geologic contacts, reservoirs, underground tanks, and voids.

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