An Investigation into Using Remotely Piloted Aircraft System Technology for Decision Making Regarding Block Lifecycle Activities in Surface Mining

By

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Presented in fulfilment of the requirements for the degree

MEng (Mining)

In the Faculty of Engineering, Built Environment and Information Technology

Department of Mining Engineering

10 December 2018

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Abstract

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Degree: MEng (Mining)

The process of mining is about executing a few, seemingly easy, routine activities with consistency and precision over an extended period of time. The research that has been conducted during the course of this study has attempted to determine whether RPAS (Remotely Piloted Aircraft System) technology (also known as drone technology) can assist operational mining staff in making better, more informed decisions regarding activities related to the physical mining process. In this study the mining process is referred to as the block lifecycle, which consists of four primary activities, namely cleaning (block preparation), drilling, charging & blasting and loading & hauling.

The study was conducted at an iron ore mine located in the Northern Cape province. To understand the benefits that RPAS technology could provide to the mine it was important to understand the baseline - the current data and information that was available to managers for the purposes of decision making. Once the research was complete, a comparison could be done between the baseline and the information that RPAS technology can provide.

During the baseline analysis it was found that activities without formal systems, such as cleaning and charging, provide a challenge for managers, as there is a lack of information from which they can make decisions. Activities performed by contractors such as drilling, loading and hauling also present an incomplete understanding of performance, as most information is available in a summarised format and is quantitative, rather than qualitative, in nature. For example, the question is posed: “did the contractor drill the planned number of metres for the day?”. A more informative alternative to that question would be: “did the contractor drill the required number of holes to the correct depth in the correct position?”. Activities where fleet management systems are used, such as the mine’s drilling equipment (Flanders ARDVARC®) and the loading and hauling equipment

(Modular Dispatch®), provide vast amounts of information on which managers can base their decisions.

In order to collect data a DJI Phantom 4 Pro RPAS unit, fitted with a 20 megapixel camera, was used to conduct flights. Each flight focused on acquiring data, in the form of photographs and/or video footage, related to a particular mining block. Flights were undertaken by qualified and authorised RPAS pilots representing a service provider called UDS (UAV and Drone Solutions (PTY) Ltd).

Once the in-field data collection process was complete, processing of the data commenced. The primary output of the data processing step was an orthophoto. The orthophoto was then processed to obtain a point cloud. Then finally, the point cloud was processed to create a digital terrain model. Additional insights were obtained through analysis in specialised software packages such as Global Mapper and WipFrag.

The study found that RPAS-generated data can provide information that will allow managers to monitor and validate progress of cleaning activities. Data related to drilling will allow managers to monitor and validate progress of drilling activities and drilling quality. Charging and blasting activities can also be assessed, as aerial imagery and high-resolution video footage can be captured before, during and after the blast. RPAS data can also be used for fragmentation analysis. Information related to loading and hauling activities can be enhanced with RPAS data, as it allows one to visually track progress and perform volume calculations that determine the amount of material which has been mined. This can only be done, provided there is sufficient data integrity that is largely controlled by ground control. RPAS technology can certainly assist managers in understanding conditions in the field and can aid better decision making for block lifecycle activities.

The application of RPAS technology in the field of mining has shown some very promising results. The extent to which it becomes entrenched, however, will depend on the appetite of the industry to adopt the technology.

ACKNOWLEDGEMENTS

The use of facilities and the financial assistance of Kumba Iron Ore are gratefully acknowledged.

I would like to thank the following persons for their contributions during completion of this dissertation:

- Johan van Heerden, Principal Surveyor at Kumba, for his guidance and support throughout the project.
- Otto Werdmuller Von Elgg of UDS (UAV & Drone Solutions) for his support and assistance.
- Craig Vorster, RPAS pilot at UDS, for his assistance in obtaining data.
- Divan de Bruyn, Managing Director at Geo Arc, for his unwavering assistance in processing data.
- Ron van Dijke and staff from the Blast Consult & Explosives Effectiveness division of Sasol who assisted with fragmentation analysis using Split-Desktop®.
- Albrecht Truter, Director at Micron Scientific, for assistance with fragmentation analysis using WipFrag.
- Antoinette Dudley, Project Manager at UDS, for her dedication and support in the data collection process.
- Jacques de Lange and Franco Grobler, of the Kolomela mine survey department, for their assistance with logistics on the mine.
- Hannes van der Walt, Rodney Wilkinson and members of the Kolomela mine blasting department.
- Professor William Spiteri for his supervision of this dissertation and advice.
- I would also like to thank Marelize and Armin for their constant love and support.

Lastly, I thank the Lord for His amazing grace.

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LIST OF ABBREVIATIONS

ASL	Air Services License
DMS	Dense Media Separation
DOH	Direct Operating Hours
DSO	Direct Screening Operation
DTM	Digital Terrain Model
FAA	Federal Aviation Administration
FMS	Fleet Management System
ft	Feet
GB	Gigabyte
GPS	Global Positioning System
ha	Hectare
Kumba	Kumba Iron Ore
LiDAR	Light Detection and Ranging
LiPo	Lithium-ion Polymer
MB	Megabyte
mp	Megapixel
m	Metre
NGO	Non-Governmental Organisation
RFID	Radio Frequency Identification
RLA	RPA Letter of Approval
ROC	RPAS Operators Certificate
RPA	Remotely Piloted Aircraft
RPAS	Remotely Piloted Aircraft System
SACAA	South African Civil Aviation Authority
UAS	Unmanned Aerial System
UAV	Unmanned Aerial Vehicle
UDS	UAV & Drone Solutions (PTY) Ltd
USA	United States of America
VOD	Velocity of Detonation

1 INTRODUCTION

1.1 Project Background

RPAS (Remotely Piloted Aircraft System) technology, also known as UAV's (Unmanned Aerial Vehicles), UAS (Unmanned Aerial Systems) or drones, is a technology that is rapidly changing the world we live in. RPAS technology has traditionally been associated with the international defence industry, but its application is gaining momentum. Very few industries these days go unaffected by its ever-increasing growth. RPAS technology has already revolutionised several industries such as agriculture, telecommunication, oil and gas, insurance, security, transportation and mining.

The adoption of RPAS technology within the mining space has been slow in comparison to some other industries. However, this trend is changing, as mining companies are beginning to see the value that RPAS technology can add to their businesses. In South Africa RPAS technology is steadily gaining popularity amongst miners, but there are challenges in introducing the technology into the mining environment, due to the rigorous requirements set out by the SACAA (South African Civil Aviation Authority) who regulate RPAS operations in South Africa.

Within the mining sphere in South Africa, the most popular application of RPAS technology at present is survey and mapping. Mine surveyors have traditionally made use of technology, such as GPS, total stations, laser scanners and LiDAR for measuring stockpiles and waste dumps, for performing in-pit surveys. These traditional methods would require a surveyor to walk or drive into the mining area. In the case of LiDAR, an aeroplane or helicopter, fitted with LiDAR technology, would be required to fly over the mining area and conduct the necessary measurements. The advent of RPAS technology has added a new dimension to the methodology by which these measurements can be performed. RPAS technology allows the mine surveying process to be far more flexible and safe, since it can conduct the aforementioned survey tasks with significantly less effort, time and risk.

RPAS technology enables surface mines to drastically increase the volume and frequency of visual and spatial data that can be collected and processed to enhance decision making. At Kolomela mine operational managers rely on data provided by existing operational systems, such as Modular Dispatch® (a fleet management system that collects data associated with trucks, shovels and some secondary equipment) and Flanders ARDVARC® (a solution which is used on the autonomous drill fleet) to assess performance and make operational decisions. These systems are also gaining advanced functionality, like high precision GPS that allows for better floor (grade) control and increased capacity to differentiate between material types and grades. However, the mine does not perform all mining operations with its own fleet of equipment. There are also a number of contractor companies who perform core mining activities such as drilling, loading and hauling. In the case of contractors there are no operational systems installed on equipment, primarily as a result of the high costs associated with these types of systems. The result is that operational managers are highly limited in their understanding and insight into mining activities performed by contractors. If one considers contractor load and haul operations the operational manager would only have an accurate indication of production performance twice in the month. This would be when the survey department performs mid-month and month-end survey measurements. There are also activities within the block lifecycle (activities that include cleaning, drilling, charging & blasting and loading & hauling), performed by the mine's own equipment, that lack adequate visibility and supervision by operational managers. One such example are the block cleaning activities that occur when a block is prepared for drilling. It is assumed that the block being drilled by one of the mine's autonomous drills is level (flat) and clean, i.e. free of obstacles such as boulders. In some cases, there may be an opportunity to take a photo of the block cleaning with a camera, but normally there is not a suitable vantage point from which to take a photo. This means that the only way for an operational manager to determine the conditions of a mining block is by conducting a physical inspection. This is not always practical, and normally the operational manager will need to rely on the word of mouth from their subordinates. These aforementioned scenarios illustrate the fact that there are opportunities within the block lifecycle to improve the quantity and quality of data that can be used for management decision making.

The primary aim of this research study is to determine the potential benefits that RPAS technology could unlock for surface operations when it comes to decision making related to block lifecycle activities. The intent of this study is firstly to investigate the current data and information landscape for block lifecycle activities. The outcome will be a thorough understanding of the data and information associated with each activity in the block lifecycle. Secondly, the intent of this study is to investigate how RPAS technology can be used to harvest data relating to block lifecycle activities and whether such data can be converted into information that can assist operational managers with enhanced decision-making capability.

The document will present conclusions regarding the gap between current management practices related to block lifecycle activities and the potential value that RPAS technology can unlock for monitoring and measuring block lifecycle activities. Recommendations on the suitability of the technology for Kumba Iron Ore will be addressed at the end of the research.

1.2 Problem Statement

An investigation to determine how RPAS (Remotely Piloted Aircraft System) technology can be used to collect data, including aerial photographs and video footage, which can be converted into information to be used by management for enhanced decision making related to block lifecycle activities.

1.3 Objectives

The objectives of this research include the following:

1) To perform a literature review in order to:
   a) Introduce the topic of RPAS so as to create an understanding of the technology.
   b) Briefly outline the rules and regulations that govern the operation of RPAS technology within South Africa.
   c) Review how RPAS technology is being applied in the broader mining context.
   d) Focus on the application of RPAS technology within the mining production cycle. The focus specifically here will be on the block lifecycle activities of cleaning, drilling, charging & blasting and loading & hauling.
   e) Review how RPAS technology has practically been used to collect data on other mining operations.
2) To collect information pertaining to current methods that are used by personnel on the mine in order to monitor, manage and make decisions regarding block lifecycle activities. These activities will include cleaning, drilling, charging & blasting and loading & hauling. The intention is to obtain a thorough understanding of the current baseline or “As-Is” state.
3) To make use of RPAS technology in order to collect data and subsequently process the data into information relating to block lifecycle activities, including the following:
   a) Cleaning (block preparation). To collect aerial photos that can be processed into an orthophoto (a series of individual photos which are matched up so that they form a new single image, consisting of all the original smaller images) that can be used to determine whether a mining block has been correctly cleaned. To process the orthophoto in order to create a point cloud (a set of data points with individual coordinates). Then finally, to process the point cloud in order to generate a DTM (digital terrain model) that can be used to determine whether a mining block is level and at the correct elevation.
   b) Drilling. To collect aerial photos that can be processed into an orthophoto that can be used to visually monitor how drilling of the block has progressed and to compare planned versus

actual hole positions. To process the orthophoto in order to create a point cloud. Then finally, to process the point cloud in order to generate a DTM that can be used to determine position of the crest of the face in relation to the first row of drill holes.

c) Charging and Blasting. To collect aerial photos that can be processed into an orthophoto that can be used to check whether material adjacent to the block has been loaded out, in order to expose the free face/s prior to blasting. To collect video footage of the blast block to confirm that the blast area has been cleared of personnel and equipment. To assess the video footage of the blast in order to check the firing sequence and detect for flyrock. To process the orthophoto in order to create a point cloud. Then finally, to process the point cloud in order to generate a DTM that can be used together with the orthophoto to confirm the success of the blast by assessing aspects such as face movement, muckpile shape, flyrock and backbreak (damage to the crest) and fragmentation.

d) Loading and Hauling. To collect aerial photos that can be processed into an orthophoto that can be used to visually monitor loading progress. To process the orthophoto in order to create a point cloud. Then finally, to process the point cloud in order to generate a DTM that can be used to measure volumes in order to determine the amount of material that has been mined from an area.

4) To draw conclusions on the gaps between current methods versus the use of RPAS technology to monitor, manage and make decisions regarding block lifecycle activities.

5) To make recommendations on the suitability of RPAS technology for monitoring block lifecycle activities for Kumba Iron Ore.

1.4 Scope of the Study

The scope of this dissertation is to collect data pertaining to block lifecycle activities which includes cleaning, drilling, charging & blasting and loading & hauling. Initially interviews will be conducted with mine personnel in order to determine the current data that is collected for each activity within the block lifecycle. Thereafter the process of collecting data for each part of the block lifecycle with an RPAS will commence. Table 1 provides a description of the data that will be collected and the processing of the data per block lifecycle activity. Additionally, Table 1 outlines the envisaged output for each set of data that has been collected.

Table 1: Planned data collection and processing per block lifecycle activity

Block Lifecycle Activity	Data Collection and Processing	Envisaged Output
Cleaning	Use RPAS to collect aerial photos that can be used to create an orthophoto.	An orthophoto that can be used to determine whether a mining block has been properly cleaned and prepared.
Cleaning	Use the orthophoto to create a point cloud and subsequently a DTM (digital terrain model).	A DTM (digital terrain model) that can be used to determine whether the block is level and at the correct elevation (grade).
Drilling	Use RPAS to collect aerial photos that can be used to create an orthophoto.	An orthophoto that can be used to monitor the drilling progress on a block. A means to compare planned versus actual hole positions.
Drilling	Use the orthophoto to create a point cloud and subsequently a DTM (digital terrain model).	A DTM (digital terrain model) that can be used to determine the position of the crest in relation to the first row of drill holes.
Charging and Blasting (Pre-Blast)	Use RPAS to collect aerial photos that can be used to create an orthophoto.	An orthophoto that can be used to check whether material adjacent to the block has been loaded out, in order to expose the free face/s.
Charging and Blasting (During the blast)	A video of the blast.	A visual means to confirm that the blast area has been cleared of personnel and equipment. A visual means to assess the blast in terms of the firing sequence of holes, flyrock, dust and fumes.
Charging and Blasting (Post-blast)	Use RPAS to collect aerial photos that can be used to create an orthophoto.	An orthophoto that can be used to visually assess aspects such as face movement, muckpile shape, flyrock and backbreak (damage to the crest) and fragmentation. A source that can be used as an input into image analysis software for fragmentation analysis.
Charging and Blasting (Post-blast)	Use the orthophoto to create a point cloud and subsequently a DTM (digital terrain model).	A DTM (digital terrain model) that can be used to assess aspects such as face

Block Lifecycle Activity	Data Collection and Processing	Envisaged Output
		movement, muckpile shape and backbreak (damage to the crest).
Loading	Use RPAS to collect aerial photos that can be used to create an orthophoto.	An orthophoto that can be used to visually monitor the depletion of material within a blasted block.
Loading	Aerial photos to create a point cloud.	A DTM (digital terrain model) that can be used to measure volumes.

It should be noted that, whilst conducting the literature survey, in some cases RPAS data was used as an input into the blast design process. This dissertation will, however, not focus on RPAS data as an input into the blast design. Additionally, this dissertation will not focus on any financial or cost related aspects associated with the use of RPAS technology.

2 LITERATURE SURVEY

There is virtually no industry that has been unaffected by RPAS. As such, there is a plethora of literature regarding the application of RPAS technology. However, when focussing on mining related applications and, in particular, the mining related application of RPAS technology within South Africa, literature on the subject is limited.

Although a review of the literature revealed that certain aspects are being investigated, such as using the outputs from RPAS's for fragmentation analysis, there were limited academic publications covering such topics. Most information pertaining to the use of RPAS technology in the mining space were short articles in mining magazine publications.

It is the authors' opinion that the primary reason for the limited availability of mining related RPAS technology application information was due to the fact that only a handful of companies are legally authorised or licensed to operate RPAS technology commercially within South Africa. As the number of companies with valid licences increases, the range of activities to which RPAS technology is applied should grow exponentially.

The aim of this literature review is to introduce the reader to the concept of RPAS technology as well as some of the most important rules and regulations impacting RPAS operations in South Africa. Additionally, the literature review addresses some of the applications within the broader mining space for which RPAS technology is being used. Thereafter more focus is placed on the block lifecycle activities in order to outline some of the work that has already been undertaken in this domain. Lastly, the literature review looks at the methodology that has been applied to other mining operations around the world in order to collect data using RPAS technology.

2.1 An Introduction to RPAS Technology

RPAS (Remotely Piloted Aircraft Systems) commonly referred to as drones, UAS (Unmanned Aerial Systems) or UAV's (Unmanned Aerial Vehicles), consist of three broad platforms or categories - namely, fixed wing (aeroplane), multi-rotor and helicopter. Examples of these can be seen in figure 1, 2 and 3.

Figure 1: An example of a fixed wing RPA (SenseFly, eBee no date).

Figure 2: An example of a multi-rotor RPA (2017, pers. comm., 15 July).

Figure 3: An example of a helicopter RPA (High Eye, 2017).

Each type of unit is suited to a particular application. Fixed wing units are primarily used for autonomous mapping when the observable area is large, such as an open pit or large waste dump. Multi-rotor units are primarily used when the pilot needs to be in control; they are more suited to local inspections, such as engineering structures or stockpiles. Commercial grade RPA's range from 600 grams to 20 kilograms and can operate at speeds of up to 100 km/h. The endurance (the duration of time for which a unit can perform a flight) is highly dependent on the weight of the unit as well as the power source. Typically, RPA's make use of LiPo (Lithium-ion Polymer) batteries that allow for flights ranging from 20 minutes to one hour. Battery technology is constantly improving, thereby extending flight times. In addition to electric (battery operated) options, there are also units that make use of small petrol engines with substantially longer flight times in the order of three to four hours. It must be noted that the current legislation in South Africa favours electric units. When considering the type of RPA to be used for a certain task it is also essential to consider the payload it will carry. There are a host of sensors that can be fitted into an RPA, including digital cameras, video cameras, thermal scanners and LiDAR units.

2.2 Rules and Regulations

The operation of RPAS in South Africa is regulated by the South African Civil Aviation Authority (SACAA), which in turn forms part of the Department of Transport. According to Civil Aviation Regulations (Part 101 of the South African Civil Aviation Regulations which form part of the Civil Aviation Act, Act 13 of 2009), the term RPAS stands for Remotely Piloted Aircraft System. It refers to a set of configurable elements consisting of a remotely piloted aircraft (RPA), its associated remote pilot station(s), the required command and control links and any other system elements that may be required at any point during flight operation (Department of Transport, 2015).

In order for a company to operate RPAS technology, there are three primary requirements that must be considered, as shown in figure 4 below.

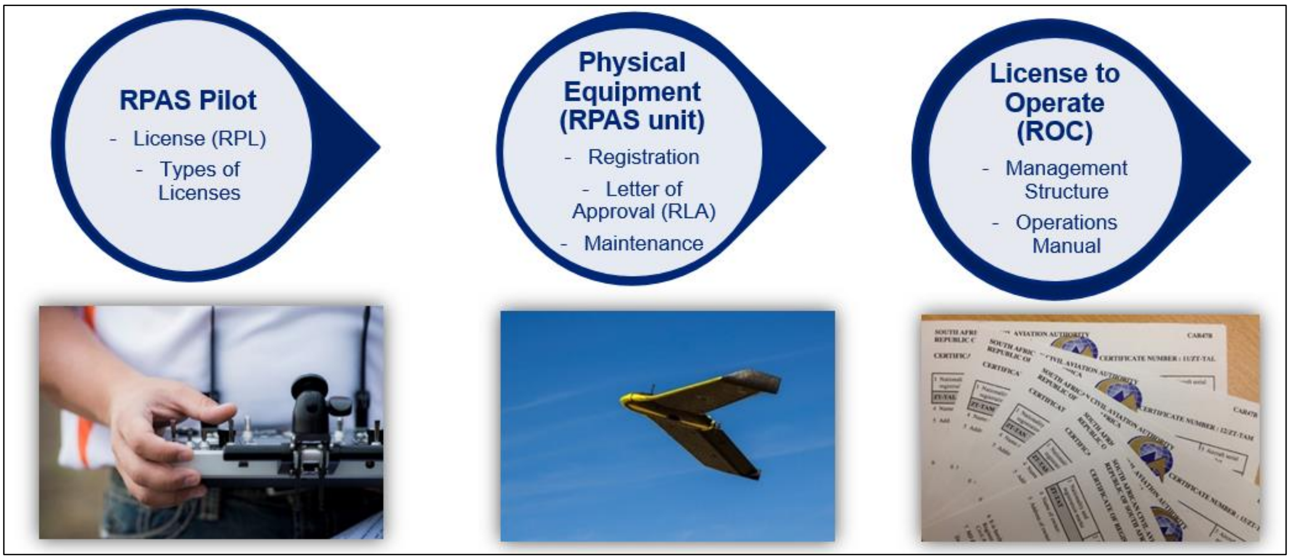

Figure 4: An indication of what needs to be in place in order to operate RPAS.

Firstly, there must be a person who is suitably qualified to operate the RPA. This person is referred to as the remote pilot and must be in possession of a valid RPL (Remote Pilot Licence). In order to obtain an RPL the remote pilot must undergo training and pass a theoretical examination as well as a practical flight examination. The RPL will stipulate which type of unit (fixed wing, multi-rotor or helicopter) the remote pilot may operate.

Secondly, there must be an RPA unit, or units that the company purchases and intends to operate. Each RPA must be classified by a set of criteria which includes, but is not limited to, the following:

- Line-of-sight, the distance that the unit is operated away from the remote pilot. There are three main categories within line-of-sight, namely:
    - VLOS (Visual Line-of-Sight) means an operation below 400 feet in which the remote pilot maintains direct and unaided visual contact with the remotely piloted aircraft at a distance not exceeding 500m.
    - E-VLOS (Extended Visual Line-of-Sight) means an operation below 400 feet, in which an RPA observer assists in the direct unaided visual contact with the RPA, in order to facilitate separation and collision avoidance requirements, at a distance not exceeding 1000m.
    - B-VLOS (Beyond Visual Line-of-Sight) means an operation in which the remote pilot cannot maintain direct unaided visual contact with the remotely piloted aircraft to manage its flight and to meet separation and collision avoidance responsibilities visually. Such operations are further than 1000m away from the remote pilot (Department of Transport, 2015).
- Height, which is the height above the surface at which the unit will be operated. The current limitation is 400ft (±120m), but exemption may be granted to operate up to 1000ft (±300m).

- MTOM, which is the Maximum Take-Off Mass that refers to the weight of the unit.

Each RPA must have a certificate of registration and must also have an RLA (RPA Letter of Approval). The RLA is issued based on an assessment by the SACAA on a number of items including, but not limited to, the following:

- the operating manual of the manufacturer of the aircraft.
- the maintenance schedule that must be adhered to.
- the performance capabilities and limitations of the specific unit.

Thirdly, in the case of an institution such as a mining company, the RPAS operator must hold a valid ROC (RPAS Operator's Certificate). There are four types of ROC's, namely commercial, corporate, non-governmental organisation (NGO) and private. When applying for a commercial ROC one will also be required to apply for an air services licence (ASL) issued in terms of the Air Services Licensing Act, 1990 (Act No. 115 of 1990). In order for an ROC to be issued, the application, which is made to the director of the SACAA, must be accompanied by the following:

- A copy of the certificate of registration for each RPA (remotely piloted aircraft) to be operated.
- A copy of the RLA (RPA Letter of Approval) for each device to be operated.
- An original operations manual (Department of Transport, 2015).

The operations manual must contain all the necessary information to demonstrate how the operator will ensure compliance with the regulations and how safety standards will be applied and achieved during operations.

Literature related to rules and regulations outside of South Africa were also investigated. In an article by (Braden, 2016) it was noted that drone technology is now far more ubiquitous, due to the fact that it's simple and cheap enough to put in the hands of the average consumer. However, governments around the world are grappling to articulate how the technology can be used. It was interesting to note the difference between the United States of America (USA) and its neighbouring country, Canada. Authorities in the USA have taken a progressive stance on the operation of RPAS technology. Here, the Federal Aviation Administration (FAA) has implemented an exemption process and regulation for commercial operations in late 2014, which has paved the way for many RPAS applications. In contrast, an article by (Braden, 2016) asserts that every part of Canada, including remote country in the Arctic, is, to some degree, a controlled airspace. And to legally fly, you have to be certified, and may have to apply for specific permission each time you fly your UAV. It also notes that Transport Canada is continuously tightening up its regulations to deter a growing number of unregistered (and inexperienced) drone operators from buzzing around areas where they should not be operating.

2.3 RPAS in the Broader Mining Context

In assessing several pieces of literature on the application of RPAS in the mining environment it was found that most technical articles focus on the application of RPAS within the survey and mapping environment where they are used for the purposes of land surveying, in-pit surveying and measuring stockpiles and waste dumps.

The use of unmanned aerial vehicles (UAVs) and off-the-shelf video and photogrammetric imaging technology are becoming more common in the mining industry for surveying. Mine mapping, stockpile volumes, blast planning and quantification are areas in which these technologies bring an added level of safety and performance, as compared to conventional survey systems. The ability to cover large areas or remote, difficult, unsafe locations prove their value (McClure, 2013).

Micro Unmanned Aerial Vehicles (µUAVs), UAVs weighing less than 2kg, can serve as highly effective air vehicle substitutes for manned planes, in that they are small, safe, easy to handle and affordable. The principle commercial application of µUAVs is short term placement of airborne sensors, e.g. camera or gas sensor, in inaccessible locations that are currently economically infeasible or too dangerous to monitor with other methods. Target missions include routine monitoring of mining operations, early information on natural disasters, and remote sensing of inaccessible or dangerous terrain. These kinds of activities are often dangerous or too physically taxing for human pilots. An example of one such activity might be updating sub-decimetre photogrammetric 3D models of mine pits at a weekly time scale to track high wall stability, production volumes and blasting efficiency (Doshi et al., 2015).

Another focus area in the mining space is the application of RPAS for monitoring environmental conditions associated with blasting. (Alvarado et al., 2015) asserts that blasting is an integral part of large-scale open cut mining that often occurs in close proximity to population centres and often results in the emission of particulate material and gases potentially hazardous to health. Current air quality monitoring methods rely on limited numbers of fixed sampling locations.

Modern UAVs are capable of producing separate air remote monitoring, video filming and aerial photography of the terrain and objects with heights of 50m to 1000m. (The SACAA currently limits flying height to 400ft, which equates to approximately 120m. Exemption may be requested to extend the maximum height to 1000ft - a height equivalent to approximately 300m). Additionally, modern UAVs can conduct thermal monitoring; measure the radiation level of atmospheric pollution to quantify the concentration of oxygen, carbon monoxide, carbon dioxide, nitrogen oxide, and/or an organic dust; and measure temperature and pressure/vacuum in the sampling zone (Danilov et al., 2015).

2.4 RPAS Applications Related to Block Lifecycle Activities

Given the broader applications of RPAS technology within the mining space have been concluded, the focus now shifts to activities within the block lifecycle. These activities include cleaning, drilling, charging, blasting and loading.

2.4.1 Cleaning

Because cleaning is the first step in the block lifecycle, it impacts on the subsequent activities, and in particular on the drilling process. Cleaning in this case refers to the process of block preparation prior to drilling activities; it includes levelling the block surface; removing debris such as boulders; and ensuring that the block can be easily accessed by drilling equipment.

The high-quality images also provide good visual assessments and measurements of block conditions and blast results that are often not possible from the blast elevation or from fixed elevated viewpoints. This information is particularly useful to pit managers, mine surveyors, planning engineers and blasting consultants (Wiseman, no date).

During the initial design phase, the top-of-bench can be surveyed, providing elevations so that drilling depths to a final grade can be accurately determined and controlled. Irregular topography with uneven, sloping and rough terrain can lead to inaccurate drilling. If the surface elevation isn't taken into consideration during the design phase, these inaccuracies may result in over and/or under-drilling. Under-drilling (short holes) causes a loss of grade control, since the holes do not reach grade or adequate sub-drilling. When boreholes are drilled too deep (over-drilling) and blasted, the bench below is preconditioned. Preconditioning of the lower bench creates oversized material, difficult drilling conditions and the potential for fly rock when the lower bench is drilled and blasted (McClure, 2013).

2.4.2 Drilling

Drilling is the second step within the block lifecycle and refers to the process whereby holes are drilled on the block, based on a specific drilling plan which specifies criteria like drill hole diameter, burden and spacing, and sub-drill.

In previously drilled patterns, the borehole positions can be audited to determine accuracy. The pattern geometry can be verified to see if it meets proposed burdens and spacings. Inconsistent patterns generate wide-ranging fragmentation, backbreak, back shatter and a significant increase in downstream costs (McClure, 2013).

Block shape, borehole locations and areas of damage are variables that can be accessed from the data. The position of holes can be detected from an orthophoto and saved as text-delimited files for use in blast planning software. Currently the software does not detect hole positions automatically and they are manually picked from the orthophoto. (Wiseman, no date).

Once the boreholes are positioned and the design finalised, the coordinates can be exported to a portable GPS rover or drill navigation system that lays out patterns with minimal time in the field spent. In operations where boreholes are not geo-referenced, the pattern can be imaged in 3D and local coordinates assigned to the boreholes. The coordinate file can then be sent to a blasting software program so that firing times can be assigned and simulations run, in order to verify performance of the firing sequence. (McClure, 2013)

2.4.3 Charging, Blasting and Loading (pre-blast, during blast and post-blast)

Charging and blasting are the third and fourth steps in the block lifecycle and refer to the process of filling drill holes with explosives; tying up the block (i.e. linking the blast holes to each other); detonating the blast; and examining the area post blast before recommencing with loading activities.

Pre-and post-blast surveys can provide valuable information to evaluate site conditions and define the performance of the blast. Distances to nearest structures and permitted boundaries can be difficult to determine with constantly changing faces and benches. Aerial imaging can provide accurate distances to ensure vibration compliance and safety. Merging the face profiles and top-of-bench surfaces into a complete three dimensional image can be used to generate in situ bank volumes (McClure, 2013).

The blast site was flown before the blast and after the blast. The information is valuable, not only for reporting purposes, but for assessing areas of blast damage, distribution of fragmentation and flyrock around a blast. As these are orthophotos with geo-referenced points, measurements can be made directly off the images (Wiseman, no date).

Post-blast surveys can provide material displacement volumes, as well as movement and swell of the muckpile. Post blast analysis of the muckpile can also be used to quantify explosive performance, timing, and pattern changes. The final wall and the power trough have typically been a challenge to survey safely with conventional systems due to inaccessibility, unsafe conditions and a limited view along the bottom of the power trough and face of the final highwall (McClure, 2013).

Reconstruction of suspect blasts can be done using much greater detailed information from images captured before and after the blast, so that performance issues can be evaluated. Photogrammetric documentation of each blast can be archived with the electronic blast records and also used to update mine maps and existing mining software programs (McClure, 2013).

Also known as a muckpile profile, a geo-referenced three-dimensional digital surface can be analysed easily for volumes and cross-sections. Accurate vertical cross-sections are generated quickly from cut-lines drawn on the surface in the survey software. An example is given where two lines automatically provide cross-sections from the 3D surface. The software generates delimited text files for analysis on other software platforms (Wiseman, no date).

Aerial drones can be used to collect fragmentation data for both blasted muckpiles and post-crusher stockpiles. In tandem with photo analysis software, drone imaging can give mine and aggregate sites a fast, accurate and economical way of benchmarking and optimising material size throughout an operation (Tamir, Wagner and Campbell, 2016).

With the advancement of unmanned aircraft system (UAS) technologies, operations are realising the benefits of new capabilities, including aerial particle-size analysis through photo analysis that uses existing UAS photographs taken for surveying and 3D profiling (Tamir, Wagner and Campbell, 2016).

Bamford has noted the following insights regarding the accuracy of image analysis methods: Image analysis methods are one of the most common methods used to measure rock fragment size distribution in mines regardless of criticism for its inaccuracy in measuring fine particles and other perceived deficiencies. The current practice of collecting rock fragmentation data for image analysis is highly manual and provides data with low temporal and spatial resolution. Using Unmanned Aerial Vehicles (UAVs) for collecting images of rock fragments can not only improve the quality of the image data but automate the data collection process. Ultimately, real-time acquisition of high temporal- and spatial-resolution data based on UAV technology will provide a broad range of opportunities for both improving blast design without interrupting the production process and reducing the cost of the human operator.

In study of image analysis accuracy, Sanchidrián et al. found that image analysis methods resulted in an error of less than 30% in the coarse region of the rock size distribution. In the same study, an error of less than 85-100% was calculated for the fine region. This means that image analysis is not reliable for fine particles. Regardless of these limitations, image analysis is still the most common method used to measure rock fragmentation in mines. The most common image analysis technique applied in mines uses 2D fixed cameras located at the base of a rock pile, on shovels and truck buckets, at crusher stations, or on conveyors in the processing plant to capture photos (Bamford, Esmaeili and Schoellig, 2017).

It is important to note that no physical scaling device is required in the images when completing a drone trial. Using ground control configurations allows users to remotely impose an accurate scaling device to the photo (Tamir, Wagner and Campbell, 2016).

Sizing analysis of muckpiles has been performed for many years. The photo analysis process involves capturing images of the fragmented rock in question and uploading these images into the fragmentation analysis software. In this case, WipWare's WipFrag 3.0 was used. Orthomosaic imaging software allows for an overlay scale to be placed anywhere in the image after the flight takes place. This scale is used as a reference inside the image, and is crucial for the analysis to take place. The photo analysis software's automatic edge detection parameters delineate the particles within the image. In this case, it took approximately ten seconds to run the analysis, and approximately seven minutes to edit manually these images in order to ensure an accurate analysis. After editing, the software outputs the particle-sizing data into a percent passing format for up to 17 customisable size classes. Unlike traditional photo analysis methods where the employee walks to a blast pile, places a measurement device in the blast pile's area of interest, and captures images standing perpendicular to the material, drone imaging allows the user to capture aerial images of the same pile, and use orthomosaic imaging to automatically set the scale inside the image (Tamir, Wagner and Campbell, 2016).

Quick and accurate measurements of size distribution are essential to managing fragmented rock and other materials. WipFrag is an automated image based granulometry system that uses digital image analysis of rock photographs and video tape images to determine grain size distributions. WipFrag images can be digitised from fixed video cameras in the field, or from using roving camcorders. Photographic images can be digitised from slides, prints or negatives, using a desktop copy stand. Digital images in a variety of formats, delivered on disk or over electronic networks, can be used. WipFrag uses powerful image analysis techniques to isolate the individual fragment boundaries. Edge detection is optimised by setting Edge Detection Variables (EDV). Manual editing can be used to improve the fidelity of edge detection. WipFrag has the facilities for zoom-merge analysis, where the combined analysis of images taken at different scales of observation can be used to overcome the size limitations inherent with a single image. Alternatively, an empirical calibration mode is available (Maerz, Palangio and Franklin, 1996).

An article on Split-Desktop® provided the following commentary on the capability of the software: The Split-Desktop® software refers to the "user-assisted" off-line version of the Split programs that can be run by engineers or technicians from their personal computers. The Split-Desktop® software allows for quantification of fragmented rock at various locations throughout the comminution process. To begin using the software, there must be a mechanism (software and/or hardware) for acquiring and downloading digital (still or video) images onto the computer. The latest software supports Fire Wire (IEEE 1394) as a method of obtaining images from video cameras that have digital video output. For digital camera images the camera software will save images into Split importable JPEG or TIFF formats. For video cameras that do not support digital output, a frame grabber is required to digitise the video signal. Split Engineering recommends the use of higher resolution images so that higher quality images can be obtained. The subject of these images can be a muckpile, haul truck, leach pile, draw point, waste dump, stockpile, conveyor belt, or any other location where clear images of rock fragments can be obtained.

Once the images are taken and saved to a computer, the Split-Desktop® software has five progressive steps for analysing each image. The first step in the program allows the scale to be determined for each image taken in the field. The second step performs the automatic delineation of the fragments in each of the images that are processed. The third step allows editing of the delineated fragments to ensure accurate results. The fourth step involves the calculation of the size distribution based on the delineated fragments. Finally, the fifth step concerns the graphing and various outputs to display the size distribution results (Bobo, no date).

In assessing the progress that has been made regarding fragmentation analysis technology, the following information was found in a brochure for a system called PortaMetrics, a patented point and shoot portable tablet (Metrics, no date):

PortaMetrics™ moves safety to the forefront of mining operations by accurately calculating rock fragmentation from a distance. Utilising stereo imaging, mine personnel no longer need to approach or climb the bench face to place scaling objects. Bench face stability can be assessed through on-board slope sensing. With three high resolution cameras integrated into a rugged industrial package and complete with a glove friendly touch screen, PortaMetrics™ is capable of capturing and processing images in any mining environment. Mine personnel no longer need to return to the office and upload images to computer software to obtain fragmentation results. Users can easily select their region of interest, capture an image and display results instantly on an intuitive graphical user interface. PortaMetrics™ includes manual correction capabilities to fine-tune images and make adjustments if necessary. PortaMetrics™ captures, analyses and produces fragmentation results in seconds - all on the portable device. Reports include rock size distribution graphs, size range statistics, slope measurements and more. Integrated GPS ensures that captured images can be quickly associated to specific blasts, while cloud connectivity allows fragmentation results to be shared remotely (Metrics, no date).

An article on fragmentation data compares the accuracy between data collected by traditional camera method and RPA and data attained through sieve analysis. The author notes that UAV technology proved to take a fraction of the time (~20%) that a conventional method takes to measure rock fragmentation (within 6% of the conventional method's accuracy). The conventional method deviates from the true distribution by up to 14% (Bamford, Esmaeili and Schoellig, 2017).

2.5 Current Methodology for Data Collection using RPAS Technology

In order to prepare for data collection using RPAS technology some of the methods that were described in literature were also reviewed so that they could be discussed with the RPA pilot prior to conducting data capture flights. The intention was to leverage learnings from other operations. Additionally, the method/s used to process data that had been collected during flying operations were also considered.

With modern high energy-density lithium polymer batteries combined with reliable satellite navigation, UAVs have become small and are able to safely carry out aerial photographic surveys lasting up to an hour. This capability makes them ideal for aerial mapping of small areas of a mine where blast specific data may be required (McClure, 2012).

By flying at appropriate altitudes above the areas being mapped, a high level of resolution can be achieved using small high-resolution (10 to 20 megapixels) commercial digital cameras. High-precision georeferenced orthophotos are thus created from a three-dimensional digital surface with accuracy relying on the placement of surveyed ground control points with sufficient elevation variance. The work in South Africa consistently achieves vertical and horizontal accuracies less than 100 mm (3.9”), with a minimum of four ground control points (Wiseman, no date).

Two software applications have been used by a South African UAV services company for the work presented in this paper. A 3D surface and orthophoto are generated from the UAV images using software to create dense and filtered 3D-data in any format from ASCII point clouds to raster GeoTIFFs or ECWs. Survey software is used to analyse volumes, cut-lines and surfaces (Wiseman, no date).

Both fixed wing and rotor aircraft are being deployed to survey mines. These remote-controlled UAV’s range in size from small model airplanes to full size aircraft. The speed, accuracy and vantage point provide a unique survey advantage (McClure, 2013).

An unmanned aerial vehicle (UAV), commonly known as a drone, is an aircraft without a human pilot on board. Its flight is either controlled autonomously by computers in the vehicle or under the remote control of a navigator or pilot on the ground or in another craft. The systems today are powered by either electric or combustion power plants. The smaller commercial systems have much lower costs than military versions, making them a viable option to own and to operate. These commercial UAV systems today feature global positioning system (GPS) guidance and image control software to capture necessary detail to generate accurate orthomosaic 3D reconstructions of the area of interest. Safety systems prevent the UAV from losing contact with the flight controller and can turn the UAV back to the controlled area prior to being out of range (McClure, 2013).

Prior to flight, the flight path boundaries are defined in the software on a satellite map that shows the actual area of the survey. Once the flight path and altitude are programmed, the UAV is launched to track the pre-programmed flight plan. Corrections are calculated and made in-flight in the event of any course deviations due to wind (McClure, 2013).

With a half-hour battery life, the UAV can cover approximately 25 hectares at 100m altitude, flying at a ground speed of 10m/sec. In six hours, an estimated 300-400 ha can be covered in a single pass flight. Flying at an altitude of 100m, each image footprint covers approximately 1.13ha area. Overlapping images provide a resolution of 3.1 cm/ pixel. Higher resolution is possible at lower altitudes with multiple passes typically done in a grid (McClure, 2013).

When on site, the drone supplier confirmed safe flying areas and configured the drone cameras. Two cameras are mounted to the drone to ensure that backup images are taken in the case of a mishap. In this case a Sony A7R 42-megapixel camera was used to complete the bulk of the imaging, with a 24MP camera as a backup. In order to take advantage of automated scaling inside the orthomosaic software, ground control using the Trimble R8 GPS surveying system capable of offering < 1mm accuracy levels was used. For orthomosaics the flight takes place at about 150ft (45.7m) above the ground, and the flight pattern allows for at least 60% photo overlap. After having safely completed the flight, the SD card with images was removed and the images were input into the photo analysis software. Photo-stitching took place off-site, and position/scaling was provided via the ground control units. This process results in both a point cloud and an orthomosaic of the data collection area (Tamir, Wagner and Campbell, 2016).

3 METHODOLOGY

The tasks associated with collecting and processing data required the student engage several role players and coordinate a variety of activities in order to meet the objectives of the dissertation. In all cases the author organised and supervised the process and then analysed the outcomes of each exercise.

Data collection activities that form the basis of this research were carried out at Kolomela mine located in the Northern Cape province in South Africa. In-field data collection was assisted with by site staff from the survey and mining departments, who assisted with transport on the mine and the installation of ground control and was undertaken between May and October 2018. RPAS flights and post flight data processing was conducted by staff from UDS (UAV & Drone Solutions (PTY) Ltd). Fragmentation analysis was facilitated by staff from two companies. Work done using Split-Desktop® was performed by the Blast Consult & Explosives Effectiveness division of Sasol. Work done using WipFrag was performed by staff from Micron Scientific (PTY) Ltd. In each case, the student was responsible for initiating contact with the relevant vendor, arranging suitable dates for the site visits, ensuring that vendors could access the mine, arranging logistics on the mine, accompanying vendors to the pit and then analysing the outputs of the piece of work that they had conducted.

Kolomela mine currently has three active pits. The mine aims to meet an ex-pit ore target of 16Mt for 2018. Mining operations are conducted by both owner equipment and contractor equipment. Ore is processed through two plants, namely the DSO (Direct Screening Operation) and the DMS (Dense Media Separation). Ore is then railed to the Saldanha port and from there proceeds to be loaded onto ships for delivery to the end client.

The methodology has been approached from two perspectives. The first perspective aims to confirm the data and information that currently exists for site staff to understand, measure performance, and make decisions related to block lifecycle activities. Each activity has been discussed individually. The second perspective explains the process by which data was collected using the RPAS. This focusses on the pre-flight, in-flight and post-flight activities that were undertaken when collecting data on site. This serves to provide the reader with a working knowledge of what is involved in operating an RPAS on a mine.

3.1 Data and Information Currently Available for Decision Making

In order to quantify accurately the potential value of RPAS technology to the mining industry, it was important to understand the current baseline or “As-Is”, i.e. the type of data and information available for each of the block lifecycle activities. Information pertaining to each activity was obtained through engagement with functional area staff. The intention was to understand in detail the kind of information typically availed to mine managers and how this information informs current decision making.

3.1.1 Cleaning

As the first activity in the block lifecycle, block cleaning bears significant impact upon the activities that follow. Its objective is to prepare the block to be drilled. This means that the block must be level (no undulations) on the correct elevation and free of obstacles such as boulders and rocks.

Block cleaning activities on the mine are performed by a dedicated team who reports to the Mine Overseer of the drilling section. In order to conduct block preparation activities, there is dedicated equipment in the form of 2 Liebherr 984 excavators with special attachments. There is also a Caterpillar D10 track dozer and a Caterpillar 992 front end loader.

Currently when a manager on the mine wants to receive feedback on block cleaning conditions there are two options. The first is through feedback from their subordinates who will confirm verbally that the block has been cleaned. In some cases, the person reporting may have some photos of the block on a mobile device as evidence. However, in most instances the location of the block is such that photos cannot be obtained. Figure 5 shows a photo of a block being cleaned and drilled simultaneously. One will note from the image that it is difficult to determine what is taking place in the area closer to the observer (denoted by the red line on the image), as the berm and highwall hinder visibility. Another aspect to consider is that the volume or tonnage that still needs to be removed by the excavator is not known. In this case the supervisor's experience will allow them to provide an estimate of how long the cleaning will take to complete, but there are a number of factors to influence their assessment.

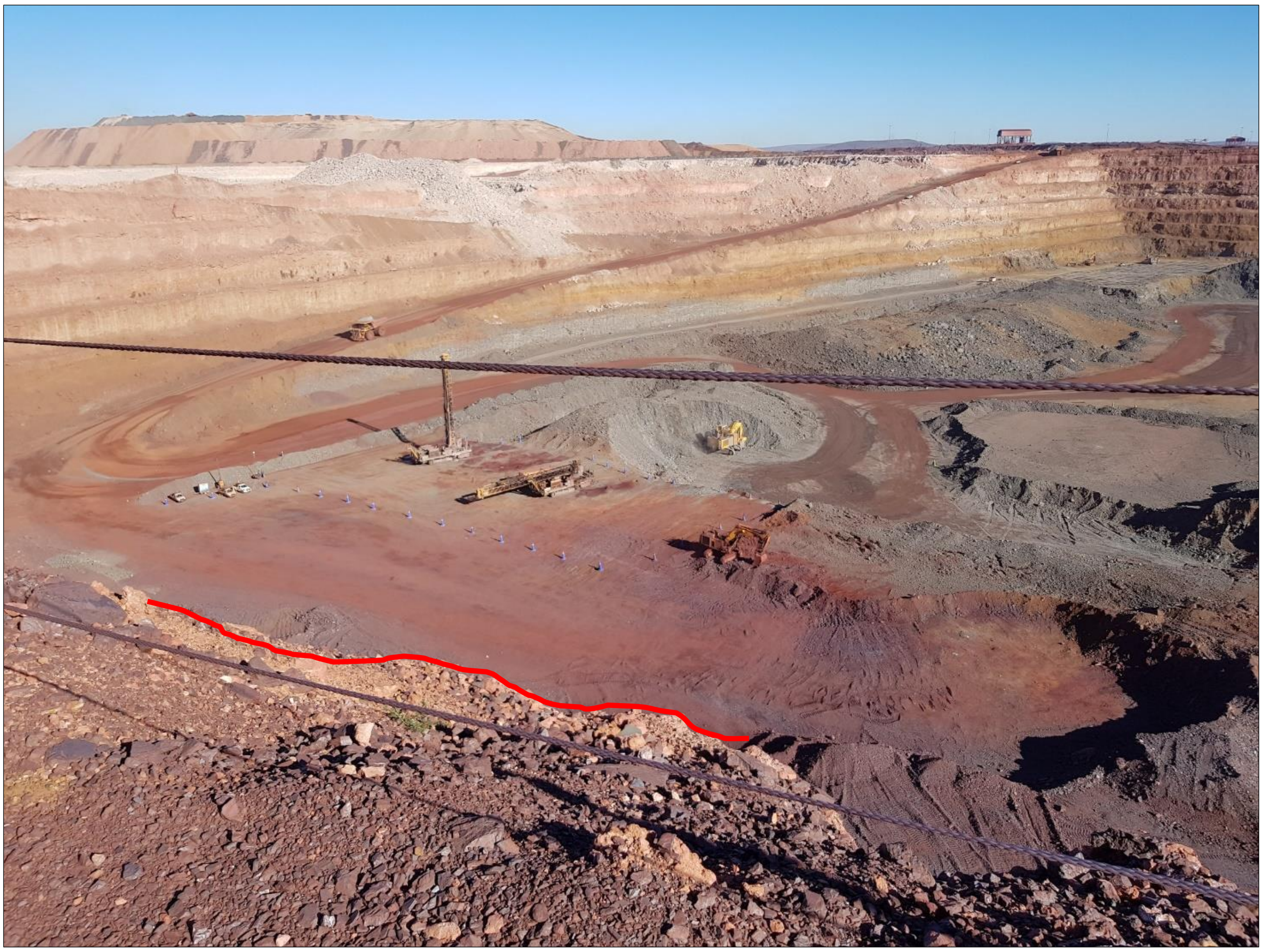

Figure 5: View of a block being drilled and cleaned from a view point.

The only other option for managers is to travel to the mining area to confirm in person that the area in question has been adequately prepared for drilling. The mine has implemented a block handover process which is aimed at ensuring quality work. For example, the block cleaning supervisor who is handing the block over for drilling will sign to indicate that they are handing over a good quality, well prepared block. The person accepting the block (in this case, the drilling supervisor) will also sign to indicate that they are satisfied with the block preparation. This works in theory but not always in practice, due to production pressures.

3.1.2 Drilling

The drilling process is the second activity in the block lifecycle. It involves the drilling of holes by a variety of drilling equipment according to a predetermined pattern that is specified by the drill and blast engineer. The primary objective is to drill holes in order for them to be filled with explosives.

Drilling activities on the mine are performed by both owner and contractor fleets. Currently the split is 80% owner drilling and 20% contractor drilling. The owner fleet consists of 6 autonomous Caterpillar MD6450 rotary blasthole drills. These drills are fitted with high precision GPS. No physical staking of blocks is done by the survey team for these drills, as the drilling pattern is uploaded to the drills over the mines Wi-Fi network. There are two contractors on site with a combined fleet of approximately 12 drills. The contractor equipment includes ROC L8 Atlas Copco, SmartROC and Sandvik DK25 drill rigs. Currently when a manager on the mine wants to obtain data or information pertaining to drilling activities there are several options. The mines CAT® autonomous drills are operated remotely from a control room located close to the mining offices. Figure 6 shows a view of the control room.

Figure 6: A view of the mines autonomous drilling control room.

This means that the manager can walk to the control room and engage with drill operators regarding drilling progress and the position/location of drills. The autonomous drills are fitted with the Flanders ARDVARC (Advanced Rotary Drill Vector Automated Radio Control) system which tracks every aspect of the drills performance. This includes machine performance metrics (rotational speed and pull down pressure) and machine health (oil temperature and air pressure). When it comes to contractor drilling much less information is available. Contractor drills cannot be seen or tracked from the mine’s control room. At present data for contractors is captured manually, although plans are in place to change this over the next few years.

The operations control department is the custodian of data and information related to mining activities, and plays a key role in informing the drilling process. This is the department which collects, collates and makes sense of the data generated by the relevant data capturing systems, the Flanders system in particular. They are also responsible for ensuring that contractor data for drilling is available for management reporting purposes. The operations control department distribute reports which provide details related to drilling activities. These reports typically summarise drill performance for the mines CAT® autonomous drills. This includes quantitative information such as equipment availability (%), equipment utilisation (%), actual metres drilled (m), average penetration rate (m/h), instantaneous penetration rate (m/h) and Direct Operating Hours (DOH). There is also a summary of the main delays for each drill for the last 24 hours.

Qualitative information related to drilling activities can be obtained from another system called BlastLogic. This is a software product supplied by a company called Maptek. BlastLogic is used as a tool for the capture of data related to survey (planned drill hole coordinates and depth), drilling (actual drill hole coordinates and depth) and blasting (quantities of accessories and amount of bulk explosives) activities. This system is not under the custodianship of the operations control department, but is the responsibility of the drill and blast engineer. Figure 7 is an output from BlastLogic which shows a plan view of the drilling accuracy, i.e. planned position versus actual position for a specific block. Figure 8 is also an output from BlastLogic which shows the drill depth adherence, i.e. the planned drill depth issued by the survey department versus the actual drill depth as measured by the Flanders system.

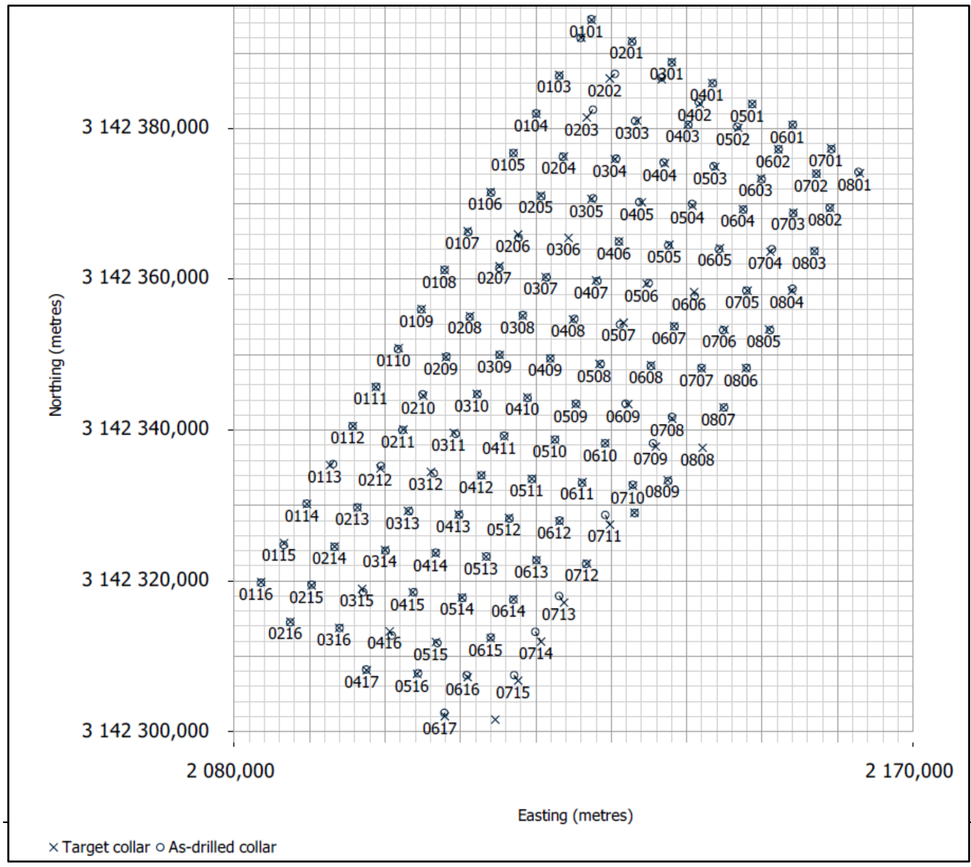

Figure 7: A view of planned versus actual drill hole positions for a block.

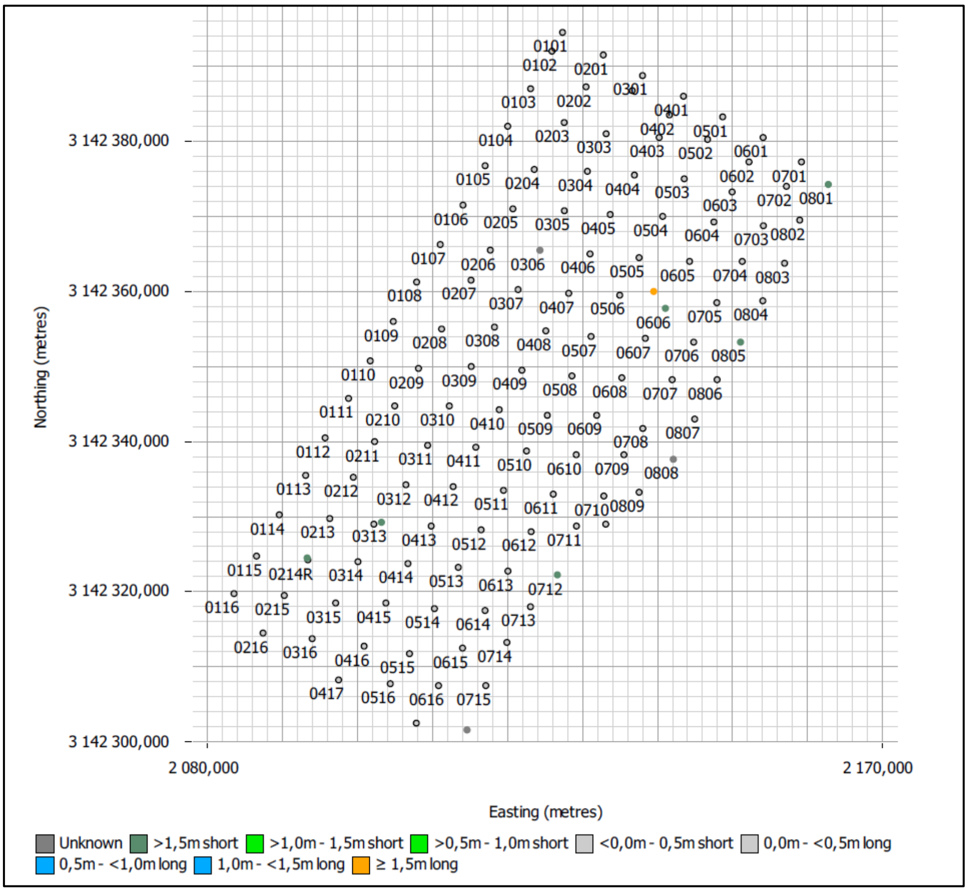

Figure 8: A view of planned versus actual drill hole depths for a block.

It should be noted that the only information available for the contractor drills is the total metres drilled per drill per shift. There is no information regarding the quality of drilling performed by contractors, as this data is not yet captured in BlastLogic.

The final option for a manager to track the progress of drilling activities is to physically visit the mining area or pit. Although this may seem unnecessary due to the plethora of data and information available through the Flanders and BlastLogic systems, it can still be very beneficial, as it provides context in terms of the conditions on the block. The manager can check safety related aspects, such as the proximity of drills to one another if there is more than one drill operating on a block. The manager can also inspect other critical aspects, such as the distance of the first row of drill holes to the crest of the block. Often drill patterns are based on planning files which do not take account of the actual position of the crest. This means that the picture in the pit can be different from the picture in the control room.

3.1.3 Charging and Blasting

The charging and blasting processes are the third activity in the block lifecycle. Charging involves filling drill holes with explosives (a detonator, booster and bulk emulsion explosive) and stemming material (normally aggregate which is placed above the explosive charge in order to seal the hole). Blasting is the process of physically detonating the blast holes to fragment the rock in order to render it suitable for loading activities.

Charging and blasting activities on the mine are performed by mine staff as well as a service provider. The service provider renders a PLTS (Prime, Load, Time, Shoot) service. Essentially this means that they are responsible for the entire charging and blasting process until broken rock is available for loading. The mine's staff play a coordinating roll and have legal responsibility for the storage and issuing of explosive products on site. The equipment fleet is made up of a service provider and owner equipment, with the former having 6 MMU's (Mobile Manufacturing Units) and the latter 2 MMU's. The mine also owns 2 stemming units. The total amount of bulk explosive used per month is in the order of 3200 tonnes.

Currently when a manager on the mine wants to obtain data or information pertaining to charging and blasting activities, there are limited options. Data and information related to charging and blasting activities are managed by the blasting team; none of this information is available in the mine's control room. The data and information are available in the BlastLogic software application, along with qualitative data related to drilling. With regards to charging there is a record of the explosives used per block. The number of accessories such as boosters and detonators are recorded on tablet mobile devices in the field. The amount of bulk explosive that is pumped into each drill hole is also recorded by the driver of the MMU (Mobile Manufacturing Unit) truck. Information recorded on the block is then available for reporting on aspects, such as powder factor and explosive density. BlastLogic also makes provision for the capture of other attributes related to blast effectiveness such as fragmentation, VOD (velocity of detonation) and muckpile profile. But this type of data is only available on an ad hoc basis, as these measurements are traditionally performed by an explosive service provider who is qualified to operate this specialist equipment and software. If a video of the blast is made the manager may be able to get a copy of the blast to review. Additionally, the blasting team may take some photos to show the outcome of a blast in terms of fragmentation.

The manager also has the option of going to the pit to observe charging and blasting activities. In the pit the manager can look at aspects, such as cleaning in front of the free face, the number of holes yet to be charged, the progress of moving equipment for the blast (moving equipment out of the blast radius), confirming explosive densities with field staff, and so on. The manager may also choose to wait for the blast to take place in order to visually inspect the area afterwards. This visual inspection will include aspects, such as fragmentation (although this is subjective in that the person cannot see inside the muckpile); backbreak (damage of the highwall behind the blast); muckpile profile (whether the profile is steep or flat); power trough (whether there is a power trough visible at the back of the block) and flyrock (how much flyrock there was and where it landed).

3.1.4 Loading and Hauling

The loading and hauling processes is the fourth and final activity in the block lifecycle. Loading involves blasted material, both waste and ore, being loaded by loading equipment (shovels, excavators or front end loaders) into haul trucks. Hauling is the process of transporting the blasted material from the loading area/block to a destination that can take the form of a crusher or stockpile (in the case of ore), or a dump (in the case of waste).

Load and haul activities on the mine are performed by both owner and contractor fleets. The mines fleet consists of Komatsu 730, Komatsu 785 and Caterpillar 777 haul trucks. These are loaded by the primary fleet of loaders, including 4 Komatsu PC 3000 shovels, a Liebherr 996 shovel and a Komatsu WA 1200 front end loader. The contractor fleet consists Caterpillar 777 haul trucks paired with 3 Komatsu PC 3000 shovels.

Currently when a manager on the mine wants to obtain data or information pertaining to loading and hauling activities there are several options. The mine's loading and hauling equipment is managed in a control room using a fleet management system called Modular Dispatch®. The Dispatch® system allows for the real-time allocation of trucks to loading equipment based on an optimisation algorithm. The system then collects data related to production activities as well as time related data associated with primary equipment. When in the control room a manager can see a rudimentary image depicting the haul road layout as well as position of equipment. Figure 9 shows the layout of the control room with the Dispatch® application displayed on the screens.

Figure 9: A view of the mines Dispatch control room.

For contractor loading and hauling activities far less information is available. The contractor equipment cannot be seen or tracked from the mine's control room. The contractors do have a simplistic RFID-based fleet tracking system in place to manage their equipment; however, this is not integrated into the mine's control room. Data pertaining to the performance of the load and haul contractor is communicated at a high level to the mine's operations control department for management reporting purposes. This typically includes a summary of the tonnes moved in a particular pit for the shift.

Another source of information pertaining to load and haul equipment is the operations control department, which is the custodian of data and information related to mining activities. This department collects, collates and makes sense of the data captured by the Dispatch® system. They are also responsible for ensuring that contractor data for load and haul activities is captured into the mine's database for reporting purposes. The operations control department distribute reports which provide details related to load and haul activities. These reports typically summarise equipment performance for primary equipment. This includes quantitative information such as equipment availability (%), equipment utilisation (%), tonnes loaded (t), tempo (t/h) and Direct Operating Hours (DOH). There is also a summary of the main delays for each piece of primary equipment for the last 24 hours. Additionally, there are reports to summarise the daily performance of each mine/pit using planned versus actual numbers. As such, there is an ongoing comparison between the planned performance of ore and waste versus the actual performance thereof. Qualitative information pertaining to load and haul activities is not readily available. Fragmentation analysis is performed on an ad hoc basis, but this is not shared extensively across the mine.

Finally, the manager has the option to track the progress of load and haul activities by physically visiting the pit. Although this may seem unnecessary due to the plethora of data and information available through the Dispatch® system, it can still be very beneficial because it provides context to the conditions of the loading area. The manager can see whether the block is being loaded out at the correct elevation. They can see whether the block is being loaded correctly and in accordance with the mine standards. For example, they will see whether there are remnants or patches of material that should have been loaded. They can get a feel for the volume of material still to be loaded from a block. The manager can also get a feel for the quality of the fragmentation on the block by looking at the tempo (tonnes per hour) at which the shovel is able to load. If the material is well blasted and the fragmentation is good, it’s likely that the shovel will load easily, and the shovel bucket will fill to an acceptable level on each pass. The haul truck will also achieve a favourable fill factor (tonnes in the bucket), which is a key measure when looking at hauling activities. The person can also check safety related aspects such as safety berms and the traffic management for the loading area.

3.2 Collecting Data for Block Lifecycle Activities using RPAS Technology

3.2.1 Overview

In order to conduct data collection activities a partnership was established with a company called UDS (UAV & Drone Solutions (PTY) Ltd). Through engagement with the staff at UDS, as well as representatives from the mine, a sensible approach to collecting data was formulated. It was decided that every time a flight was undertaken on site it would be done with the purpose of collecting data related to one of the four block lifecycle activities - namely cleaning, drilling, charging & blasting or loading & hauling. The idea was to focus on a few individual blocks so that data for their lifecycles could be collected. The data collection process was aimed at collecting data that could satisfy the initial objectives of the project.

The DJI Phantom 4 Pro was selected as a suitable tool to harvest data. The Phantom 4 is a multi-rotor unit that is equipped with a 20 megapixel camera. It also has ideal video capability for the purposes of the project. Figure 10 shows a photo of the DJI Phantom 4 unit.

Figure 10: The DJI Phantom 4 Pro unit that was used for the purposes of data collection.

One of the key considerations when collecting data using the RPAS was to ensure sufficient ground control in order to facilitate the processing of data after the flight. Ground control points (GCPs) are an integral part of aerial mapping and help to ensure a high degree of accuracy by allowing the coordinates for each point on an aerial photograph to be calculated. If there is not sufficient ground control the data will not be suitable for volume calculations. The ground control points used on site consisted of pieces of conveyor belt (400mm by 400mm) that were accurately surveyed in, with a GPS, by a surveyor. Figure 11 below shows a photo of a ground control point being surveyed in.

Figure 11: A surveyor on the mine measuring in a ground control point with a GPS.

The process of collecting data was routine and included pre-flight preparation, flight mission execution and post-flight processing.

3.2.2 Pre-Flight Preparation

The process commenced with pre-flight preparation. Two components were involved - namely, office preparation and site preparation.

Office preparation included the completion of a number of administrative tasks mostly associated with ensuring safe operation of the RPAS. Documents included:

- A risk calculation sheet which is a pre-site risk assessment.
- An offsite risk assessment to identify risks and determine mitigation actions.
- A maintenance log for the RPAS which tracks the number of hours an RPAS has been operated and determines service intervals.
- A briefing sheet that is used for briefing the team involved in the field such as observers, spectators and the payload operator.
- An emergency number verification sheet which lists all the main emergency services (hospital, police, fire services, nearby airports) for the area. Each entity must be contacted to verify that the contact details are valid.
- A job feasibility and safety assessment that diagrams the area of operation. A template of this document has been included as Appendix 1.
- Landowner's permission, which is a document from the owner of the land that grants permission for RPAS flights to take place.
- A health statement declaring that the pilot is feeling well to operate the RPAS. No alcohol is permitted 8 hours prior to duty. No medication, including prescribed medication, is allowed.
- Special instructions which are normally applicable to an area not flown on a regular basis, such as an event where members of the public will attend if one operates in controlled airspace.
- A site process document which provides a description of a number of items related to the location where RPAS operations will take place. A template of this document has been included as Appendix 2.
- A mini risk assessment to highlight any other risks/hazards that were not identified in the initial offsite risk assessment.
- The pre-flight checklist which lists a number of items that the pilot must confirm prior to operating the RPAS. A template of this document has been included as Appendix 3.

Site preparation focused on the area where the flight was to take place and included the following:

- Identifying the specific area to be investigated, such as pit, block, waste dump or stockpile.
- Determining a suitable launch area for the RPAS. Due to a multi-rotor being used, there was more flexibility, as less space for take-off and landing was required.

- Obtaining the necessary permits/authorisations to enter and exit the area safely. The project team was always accompanied by a mine representative to ensure safety.
- Upon arrival at the launch site the equipment was set up. This included the ground station, charging bay, RPAS and launch area. Figure 12 and Figure 13 show the typical arrangement in the field.
- A site briefing of the team involved in the flight. This was done using the briefing sheet prepared for the office preparation.
- Finalisation of the flight plan which included the confirmation of flight parameters, such as altitude (flying height specified in metres above the elevation from which the RPAS takes-off), % overlap (80%) and % side lap (75%). Overlap is expressed as a percentage and indicates the shared area between two photos on the same flight line. Side lap is also expressed as a percentage and indicates the shared area between two photos in adjacent flight lines. The system would then adjust the flight speed in order to prioritise the other parameters, thus ensuring that all images could be captured. The flight plan also confirmed the size of the area (on average 1.2km^2 for this study) to be flown which in turn dictated the number of batteries to be used to complete the mission. In most instances between three and four batteries where required to fly the area where data was being collected. This meant taking off and landing the RPAS several times per mission.
- Checking and confirming all other flight parameters such as GPS health, battery capacity and so on.
- Performing a radio call. This involved a blind broadcast to aircraft in the area where the flight was to take place. Aspects such as location, altitude and duration of the flight were communicated.

Figure 12: A ground control station on the back of a mine vehicle.

Figure 13: A take-off zone in the field.

3.2.3 Flight Mission Execution

During the flight mission execution, the pilot undertook to fly the aircraft in a consistent and safe manner. The pilot performed the take-off procedure and navigated the craft to the desired altitude. Once this was accomplished the RPAS entered an “auto” mode where it simply executed the flight plan instruction that had been uploaded. During the course of the flight the pilot would monitor vital statistics such as flying height, speed and battery life, which were displayed on the screen of the flight controller. He would also confirm that images were being acquired as planned and monitor the radio traffic in case another aircraft communicated its presence. Figure 14 shows a view of the display as seen by the RPAS pilot when the flight is being executed. The flight plan can clearly be seen (the blue lines in the centre of the display), as can the vital statistics on the left-hand side. The image displayed on the top right-hand side is a live view from the unit.

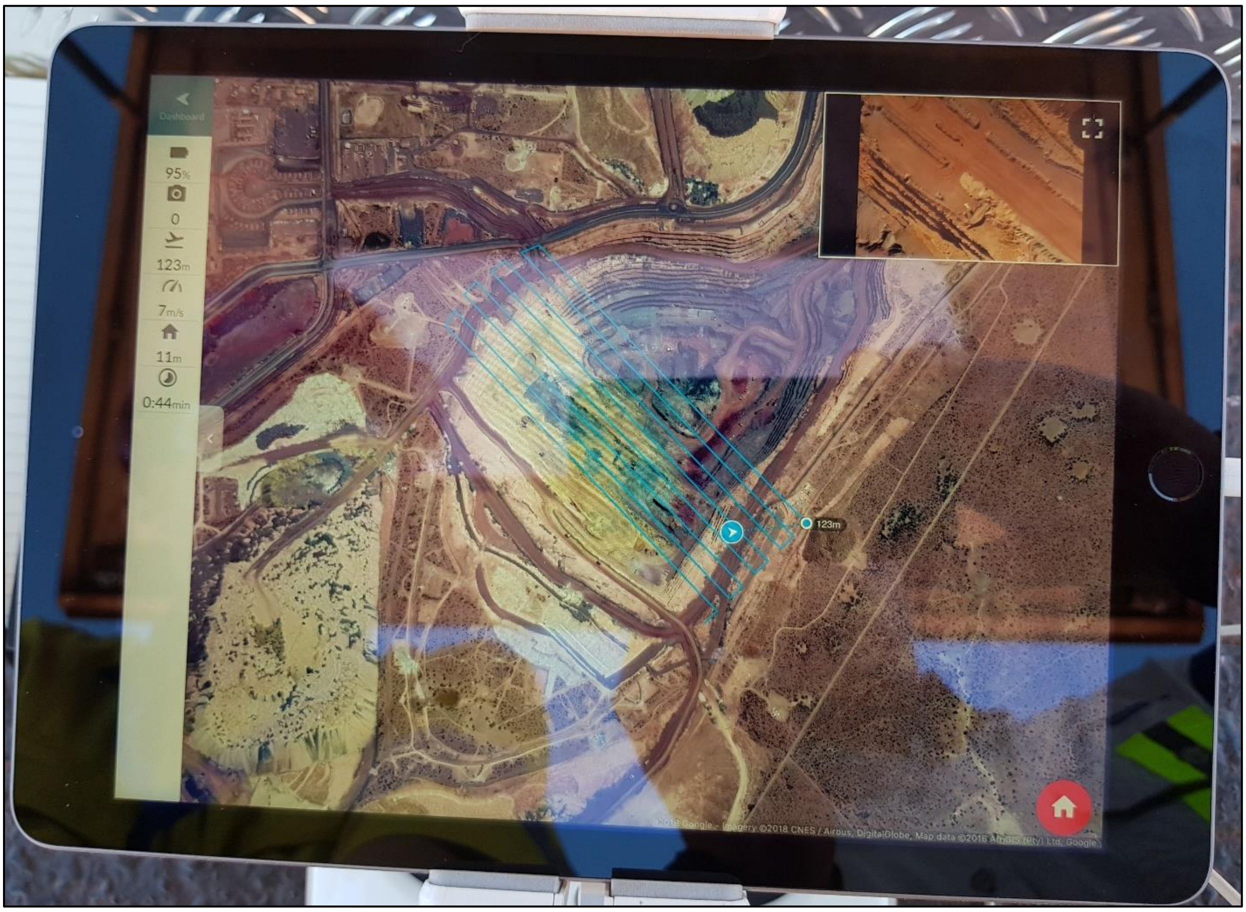

Figure 14: A view of the display screen as observed by the RPAS pilot when flying.

In general, flights for the purpose of data collection were executed from the same location; the only difference was that the life cycle activity took place on the block, i.e. the block transitioned from being cleaned to drilling to charging to loading. However, when data related to blasting was collected, the location had to change due to proximity to the blast block. The team discussed a suitable option with the blasting foreman and relocated accordingly. On the day of a blast the objective was to capture three sets of data. Firstly, the block was surveyed prior to blasting. Then a video of the blast was undertaken before, during and after blasting. Finally, a flight to collect data for the purpose of fragmentation analysis was executed.

The approach regarding fragmentation analysis had to be adapted a few times until a suitable method became evident. Initially, representatives from Blast Consult & Explosives Effectiveness division of Sasol assisted the pilot with imagery collection. The intention was to have the Sasol team conduct traditional fragmentation data collection and then have the RPAS pilot apply the same method using the RPAS. The imagery collected for each method would then be processed and analysed by Sasol. The reason for this approach was due to Sasol making use of the Split-Desktop® image analysis software package. Split-Desktop® is the most widely used image analysis software in the South African mining industry. The primary principle to Split-Desktop® is that images must include reference objects within the photograph. Figure 15 shows a Sasol representative taking photos of the blasted material for the purpose of fragmentation analysis, with two soccer balls as reference objects.

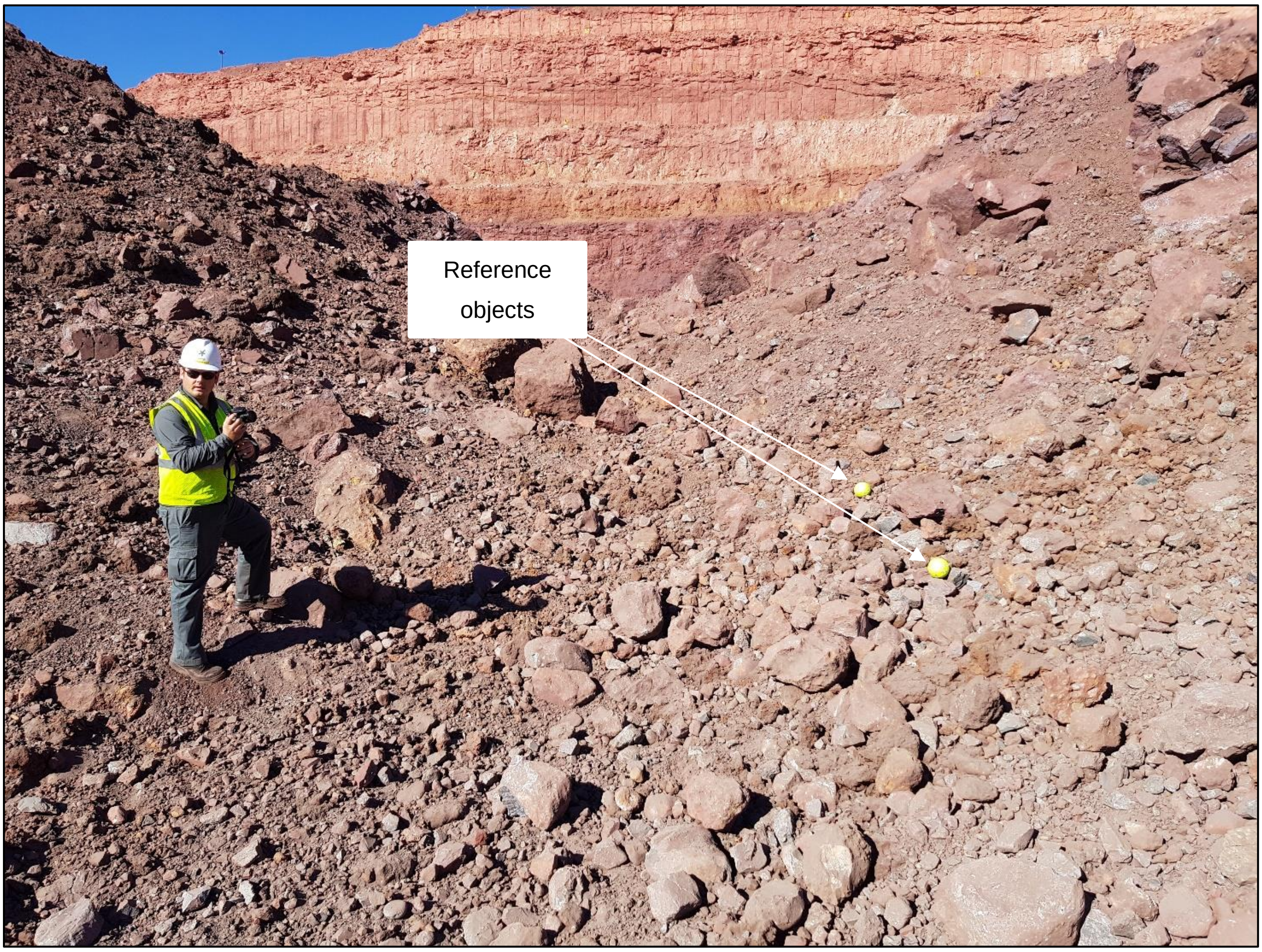

Figure 15: A Sasol team member collecting fragmentation data in the field.

Figure 16 shows the RPAS pilot taking photos of the blasted material for the purpose of fragmentation analysis. The results and analysis of this method will be discussed in the next chapter.

Figure 16: The RPAS pilot capturing fragmentation data in the field.

It soon became apparent that the initial method was not ideal, due to a large discrepancy in results between the traditional method and the RPAS. The reasons for this will be discussed in the results and analysis portion of the document. The second tested approach was to use a different software package for the fragmentation analysis. It was decided to make use of WipFrag, which has the capability to process orthophotos generated from RPAS imagery. The benefit to this approach was that we could apply the same method as was previously used in collecting data for all the other steps in the block lifecycle, (i.e. the pilot did not have to do anything different to what he was used to). This method appeared promising, but a few challenges had to be overcome. Although the method for collecting data remained the same the flight parameters had to be adjusted. In particular, the flying height of the RPAS above the blasted material had to be reduced in order to generate an orthophoto of sufficient resolution to perform fragmentation analysis.

3.2.4 Post Flight Processing

The post-flight processing commenced once the RPAS had successfully landed and constituted a number of tasks. The data card that collected and stored data on the RPAS during the flight was removed and inserted into a computer. The relevant files were then transferred from the data card to the device. Additionally, a file containing data on the location of ground control points was obtained from the survey department.

A software application called Agisoft PhotoScan Professional was then used to perform initial processing of the data. This included the following steps:

Step 1. The first step involved importing the photo and ground control point (GCP) data. Figure 17 shows all the photos, represented by the blue circles, and the ground control points, represented by the light blue flags.

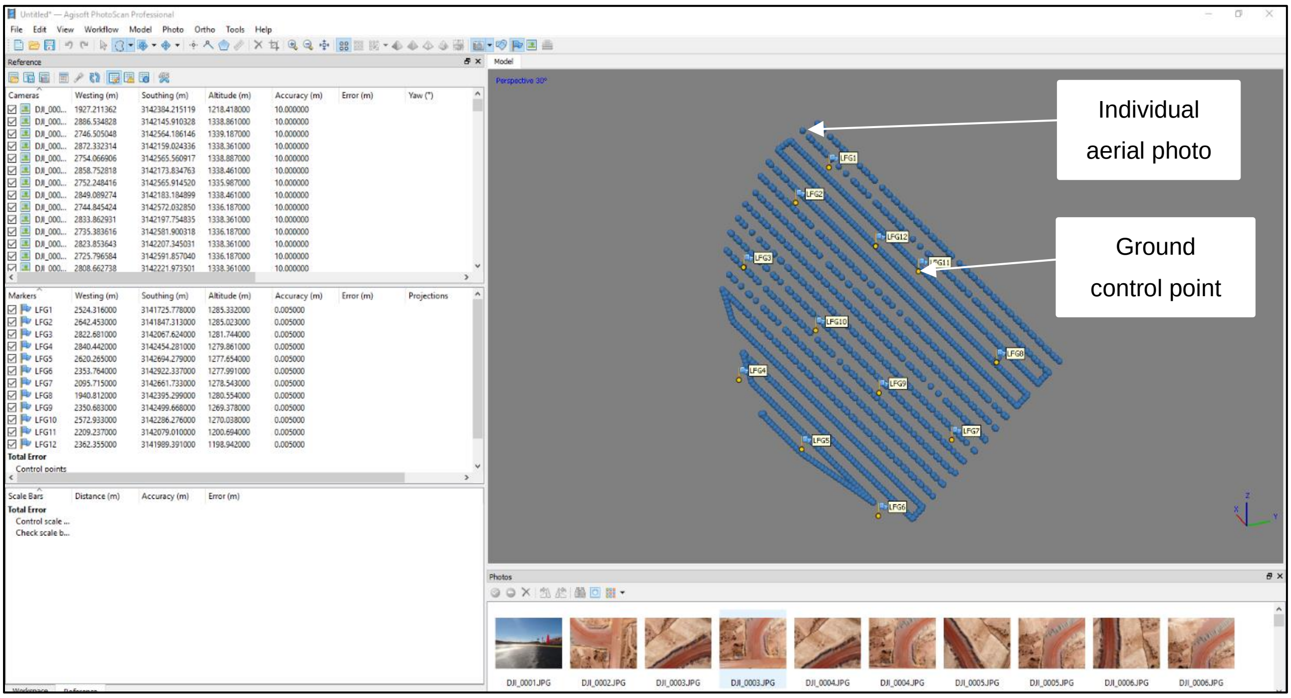

Figure 17: A view of individual photos and ground control points.

Step 2. The second step involved correcting, also referred to as georeferencing, the images. Each photo/image has a coordinate from the GPS on the RPAS. This must be corrected by referencing the known points, i.e. the GCP's. Figure 18 is a screenshot depicting the process of correcting an image. The process of correcting images is very time consuming and is the most manual portion of the initial data processing.

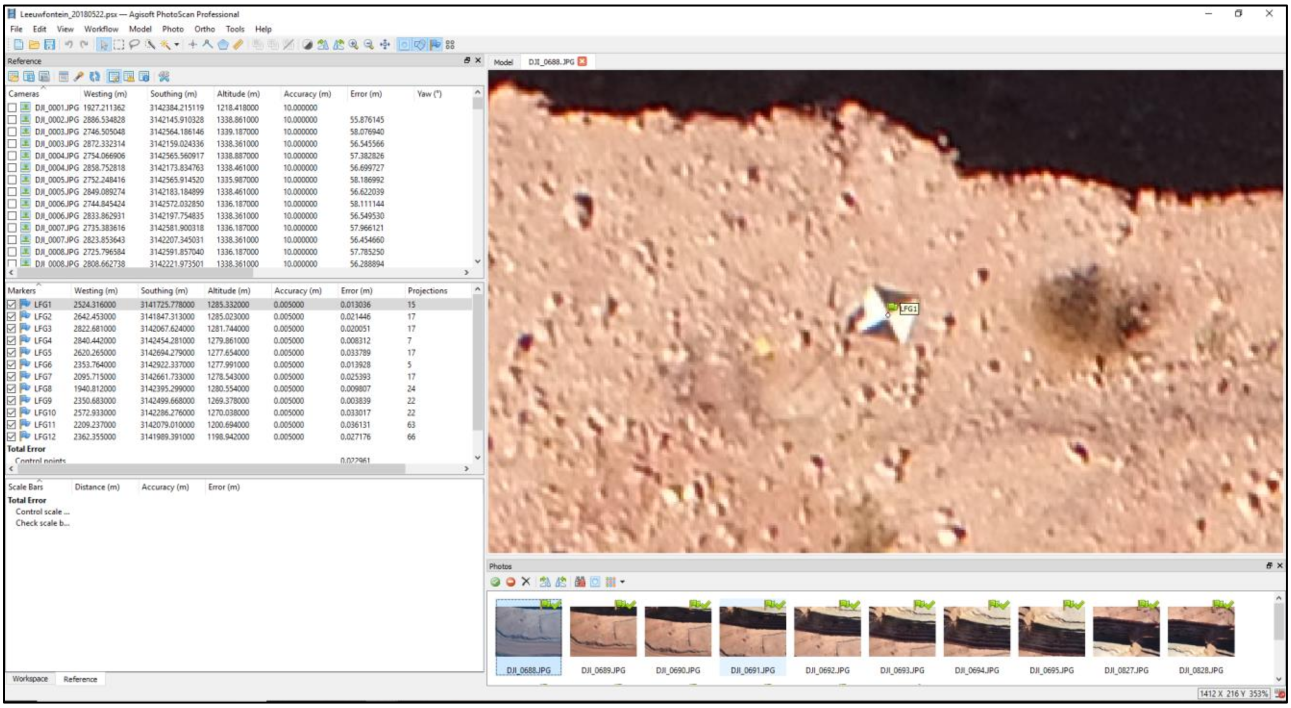

Figure 18: A photo showing the location of a ground control point in the pit.

Step 3. Once the correction of images had taken place an orthophoto (figure 19) could be created. This was the process of stitching together or merging all the individual photos into a single photo. The orthophoto was then exported GeoTIFF file.

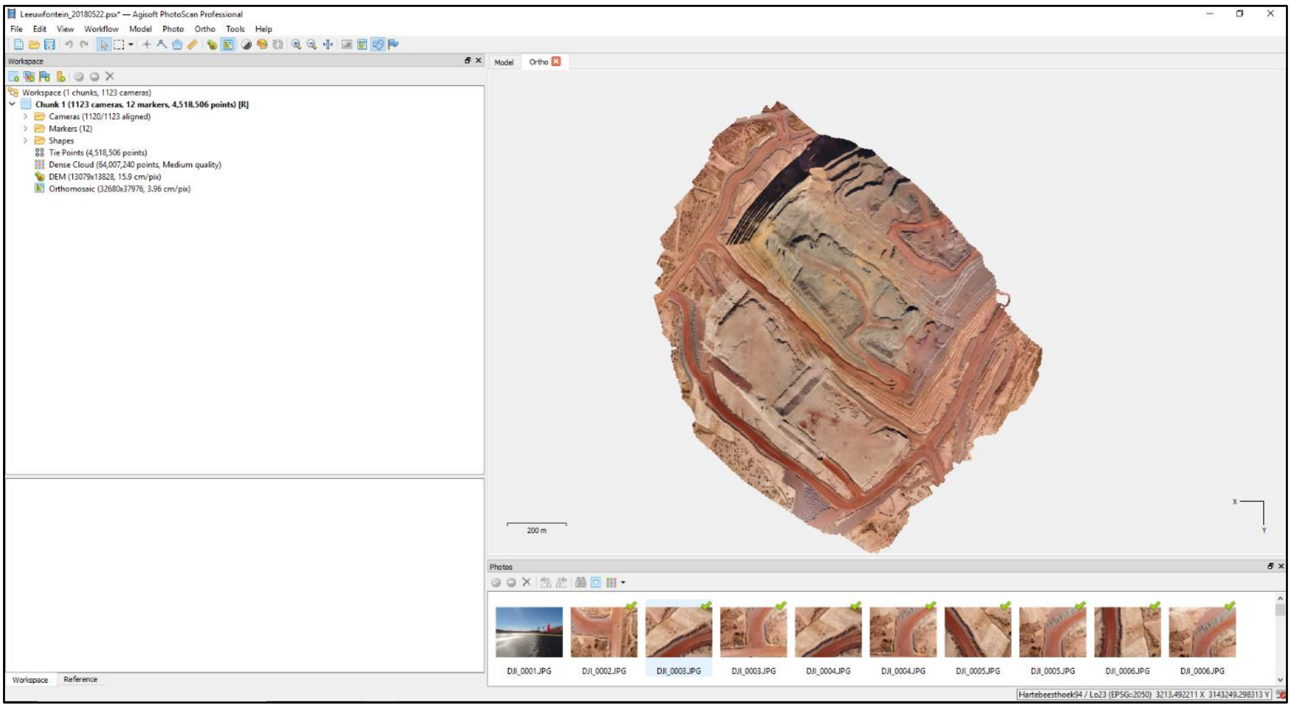

Figure 19: An example of an orthophoto.

Step 4. The orthophoto could then be processed further in order to generate a sparse point cloud (figure 20).

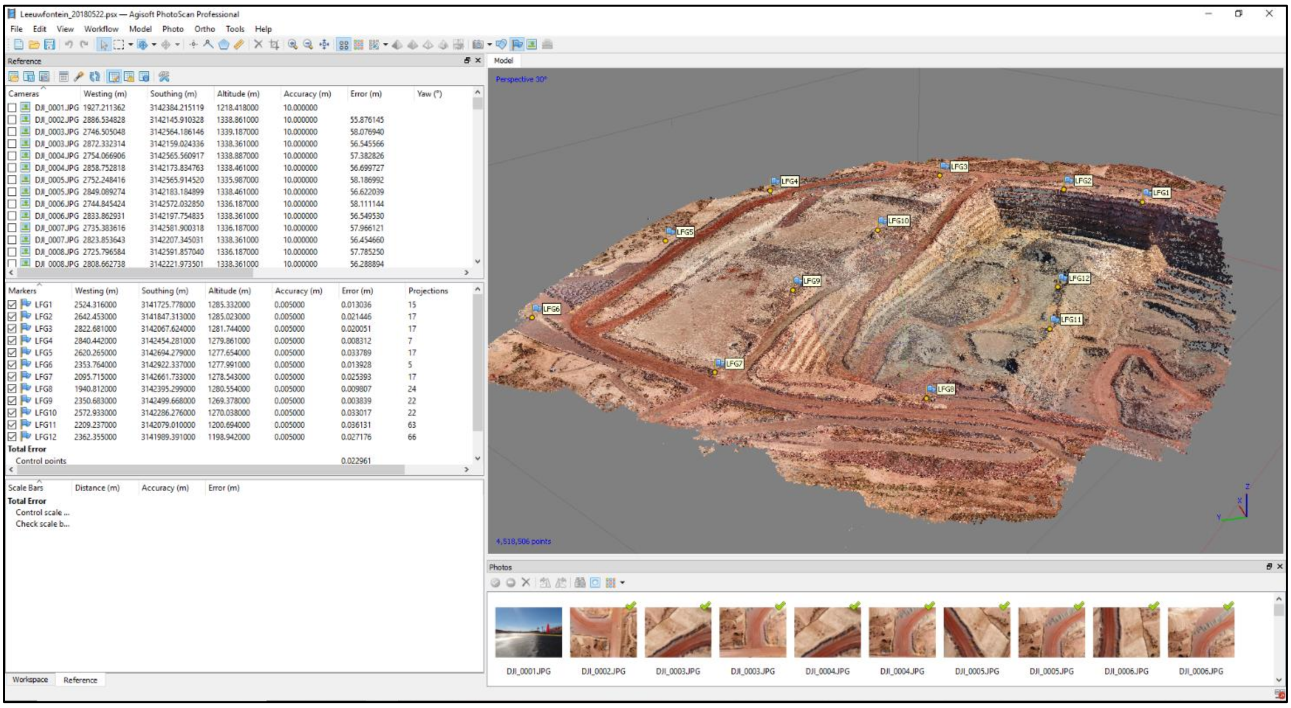

Figure 20: An example of a sparse point cloud.

Step 5. The next step was to generate a dense point cloud (figure 21) in the software. One can see that the image becomes more clear and realistic.

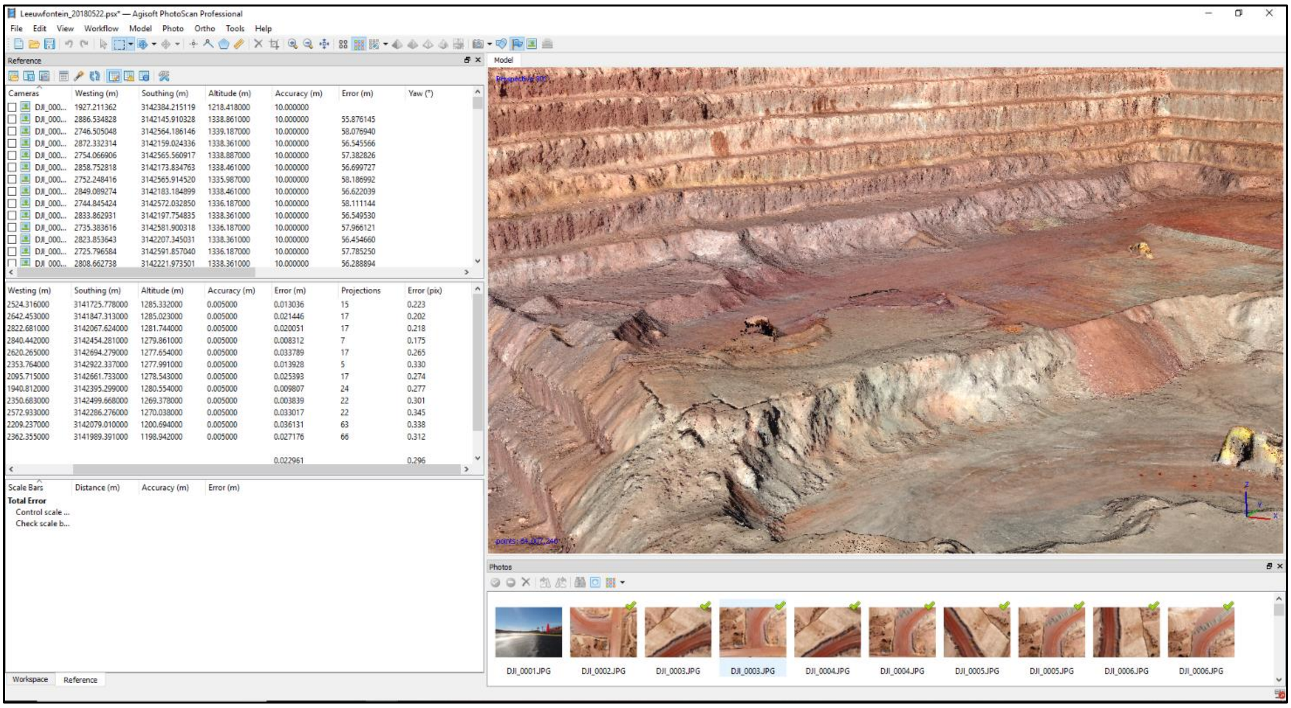

Figure 21: An example of a dense point cloud.

Step 6. This step involved scrutinising the dense point cloud and removing objects such as vegetation and equipment that could impact aspects like volume calculations during analysis.

Step 7. Once the data had been vetted and cleaned one could generate a DTM (Digital Terrain Model). Figure 22 shows a view of the DTM that was generated. The variation in colour in the image is related to changes in elevation. The DTM gets exported as a TIFF, BIL or XYZ file.

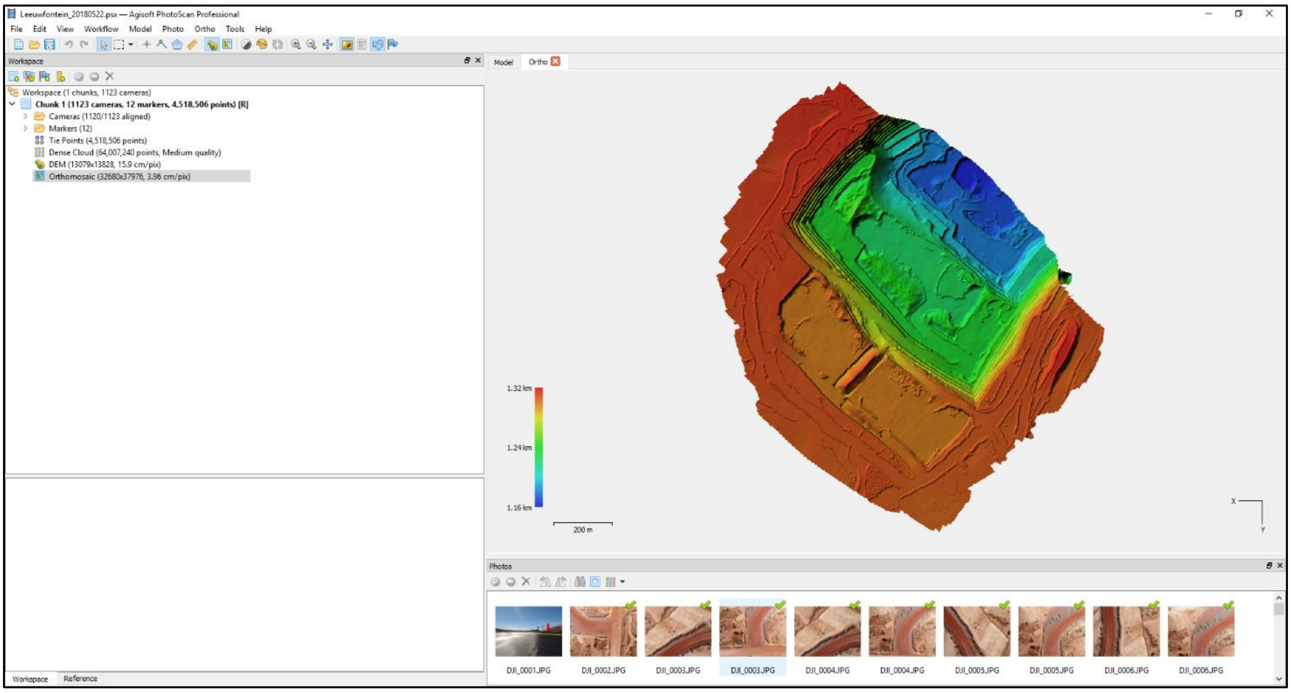

Figure 22: An example of a DTM (Digital Terrain Model).

A Photogrammetry Processing Report containing a very detailed summary for the entire mission could then be generated in PDF file format. The report included information related to technical aspects, such as:

Survey data – number of images, flying altitude, ground resolution, coverage area.

Camera information – camera model, resolution, focal length, pixel size.

Ground control points – number of GCP's, error estimates.

DTM information – resolution, point density.

Table 2 shows some technical statistics that appear in the reports.

Table 2: Technical statistics from Photogrammetry Processing Report

Number of images:	1123	Camera stations:	1120
Flying altitude:	156 m	Tie points:	4 518 506
Ground resolution:	3.96 cm/pix	Projections:	20 808 566
Coverage area:	1.21 km²	Reprojection error:	0.666 pix

Once the data processing in Agisoft was complete the next step was to import the orthophoto and DTM into a GIS software called Global Mapper. Figure 23 and 24 show the imported orthophoto and DTM respectively.

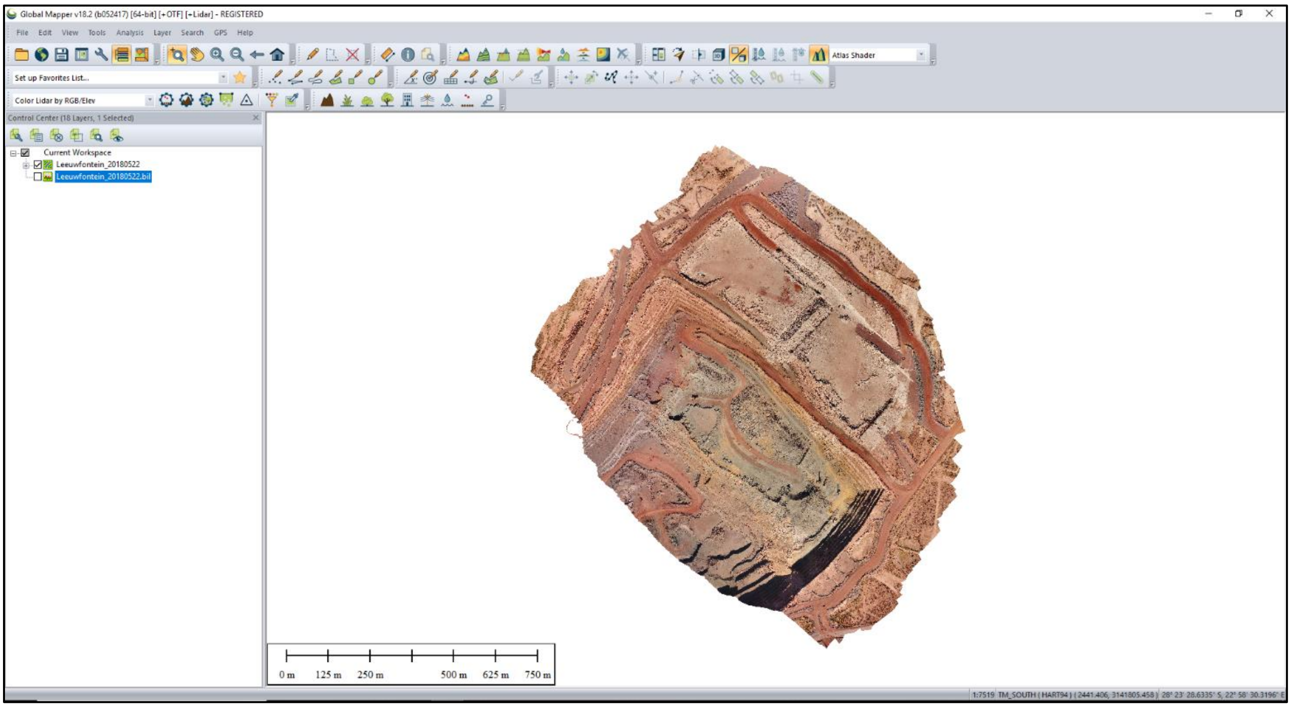

Figure 23: An orthophoto in Global Mapper.

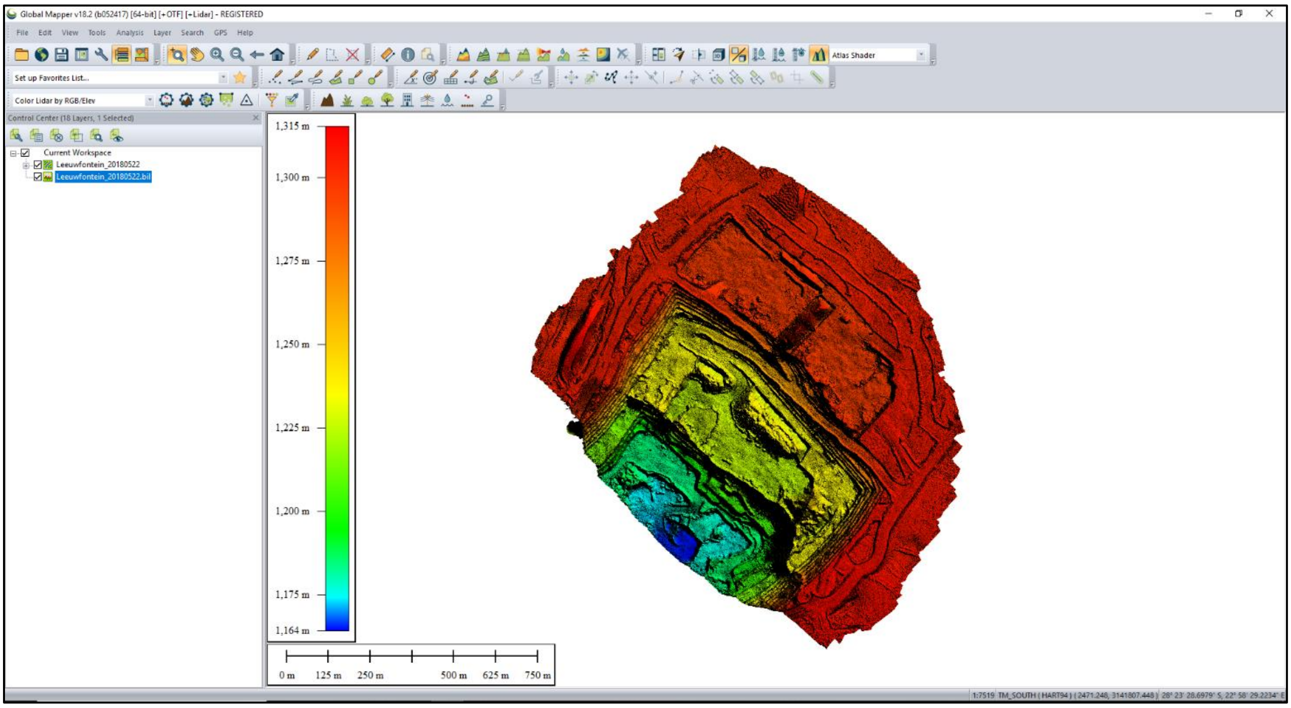

Figure 24: A DTM in Global Mapper.

Once the files had been imported into Global Mapper an analysis could be performed. This will be discussed in detail in the results and analysis portion of the document.

The total time taken to complete each mission (comprising time taken for the pre-flight preparation, flight mission execution and post-flight processing) was substantial. Time associated with pre-flight preparation included all office-based activities as well the time taken to travel to the site where the flight would be executed. The average time spent on pre-flight preparation was in the order of two hours. Time associated with flight mission execution included the time taken to set up in the field and the time taken to physically execute the flight mission. It also included packing up equipment after the flight and travel time back to the office. The average time spent on flight mission execution activities was 1.5 hours. Time associated with post-flight processing included the time taken to transfer data from the data card to a computer as well as the initial processing of data in Agisoft PhotoScan Professional. The average time spent on post-flight processing was six hours. Thus, a total time of about 9.5 hours was required from start to finish to process a single set of data. In total, approximately 20 sets of data were collected for this research project.

4 RESULTS AND ANALYSIS

The results and analysis portion of the study will focus on data related to two blocks, namely LFP0914O107 and LFP1114O111 located in the Leeuwfontein pit at Kolomela mine. Figure 25 shows an aerial view of the pit with the approximate location of blocks indicated by the blue shaded area.

Figure 25: Leeuwfontein Pit with the research area shaded in blue.

The results of the data collection process will be discussed in relation to the relevant block lifecycle activity.

4.1 Cleaning

The outputs that were envisaged as part of the objectives related to cleaning and block preparation can be seen in Table 3. The block identified for tracking of cleaning activities was LFP0914O107.

Table 3: Details for data related to cleaning activities

Block Lifecycle Activity	Data Collection and Processing	Envisaged Output
Cleaning	Use RPAS to collect aerial photos that can be used to create an orthophoto.	An orthophoto that can be used to determine whether a mining block has been properly cleaned and prepared.
Cleaning	Use the orthophoto to create a point cloud and subsequently a DTM (digital terrain model).	A DTM (digital terrain model) that can be used to determine whether the block is level and at the correct elevation (grade).

Once data pertaining to cleaning activities had been processed, results as depicted in Figure 26 and Figure 27 were typically available. These two orthophotos show the progress of cleaning activities for the block. The planned block outlines are indicated in light blue, green and yellow. The block of interest is the one outlined in light blue. By comparing the two images, progress of cleaning activities on the block can easily be seen. One can see that the block looks reasonably well prepared in the lower portion, but in the upper portion there is a lot of material that still needs to be loaded out and cleaned. Based on figure 27 it can be seen that the block is being drilled by two drill rigs. It can also be seen that drilling of the block commenced before the whole of the originally planned block was cleaned. It likely indicates that a decision has been taken to "cut" the block, which means only a portion of the originally planned block will be drilled. This mostly happens in instances where teams are under pressure to meet production targets. Additionally, one can see that there is blasted material adjacent block that should be loaded out prior to the block being blasted.

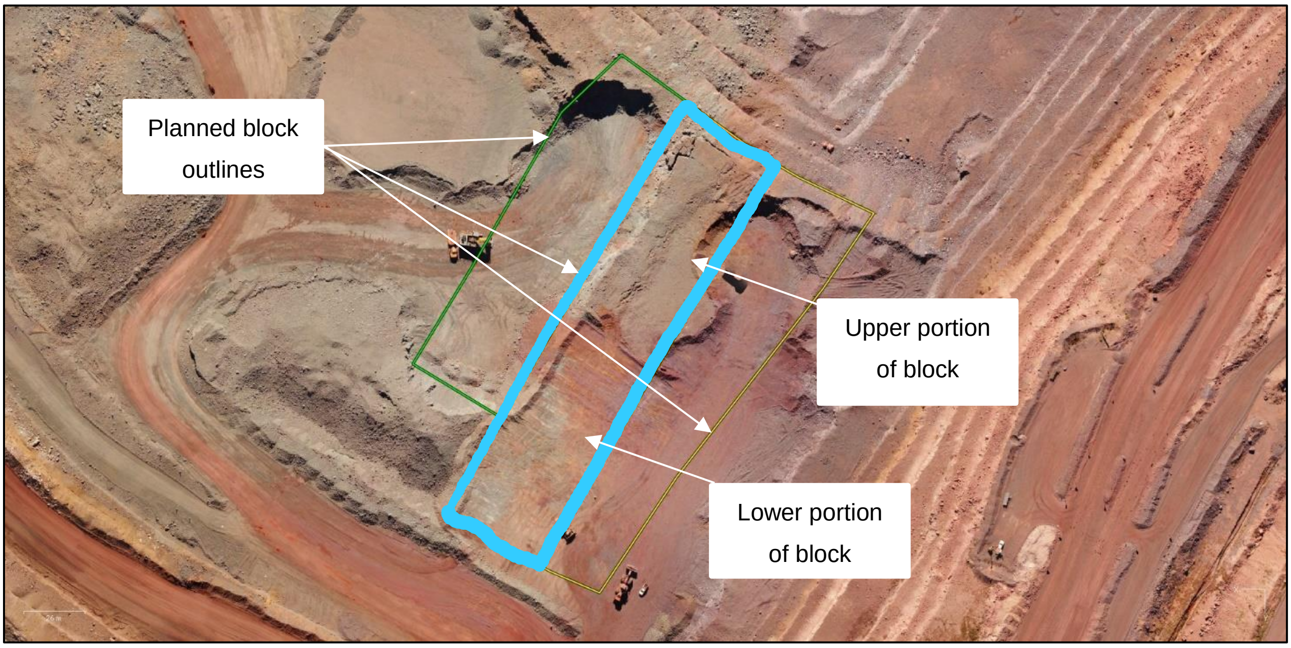

Figure 26: An initial orthophoto showing the status of block preparation on 22 May 2018.

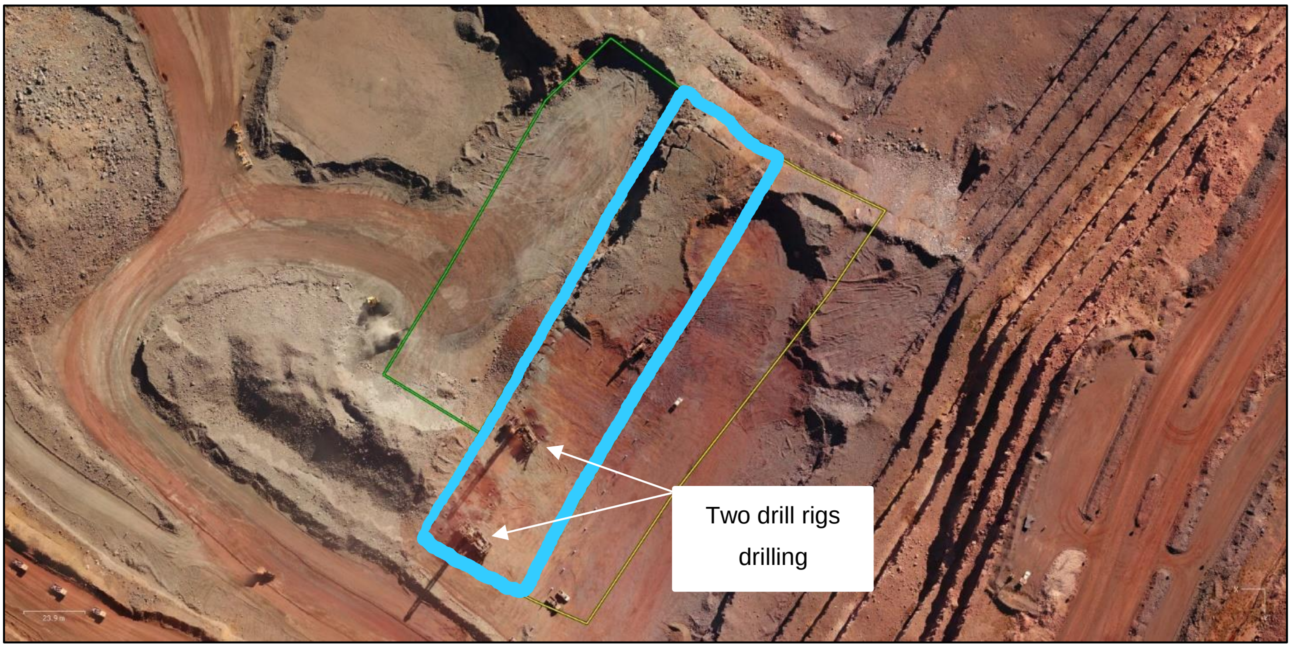

Figure 27: An orthophoto showing the start of drilling activities on 23 May 2018.

Figure 28 shows a 3-dimensional view of the block where the orthophoto has been draped over the DTM. This is a static image in this document, but if one opens the DTM in an appropriate software package, such as Agisoft, then one can rotate and view the block from any angle or vantage point. From the image one can clearly see that there is a significant amount of material in front of the free face that needs to be loaded out prior to the blast taking place.

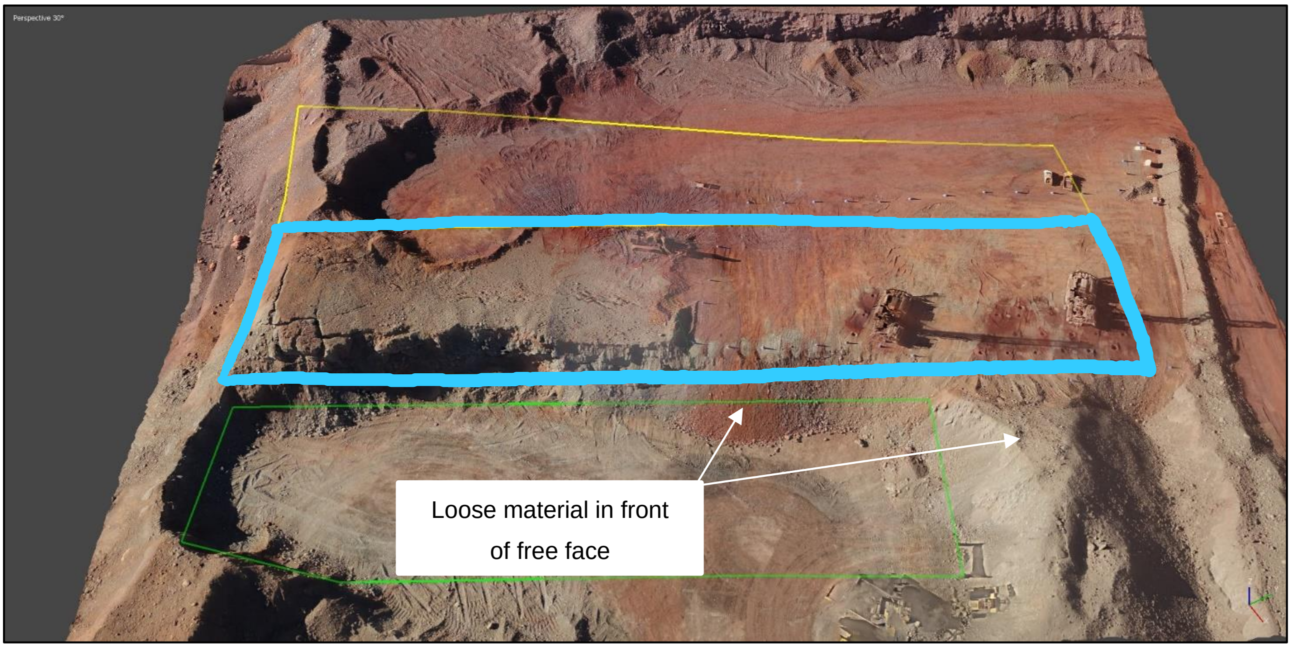

Figure 28: A 3-dimensional view of the block depicting block status.

Another important aspect to be considered in the block preparation process is the block elevation. In this instance the level of the floor where drilling is going to take place is meant to be 1210 metres above mean sea level. Figure 29 shows a view of the elevation of the area in and around the block. The colours denote the elevation and are set at 1 metre intervals. The area shown in light blue indicates where drilling activities are planned to take place. From the image it is apparent that the planned drill area is mostly green, which indicates that the elevation is between 1210 metres and 1211 metres. This is an indication that the planned elevation has been well adhered to when the previous block was loaded out. Figure 30 shows section AA through the block (depicted as the red line in figure 29). From this one can see that the floor elevation looks acceptable and that there are minimal undulations on the block. On the left-hand side of the image one can see the “bump” which indicates the safety berm. On the right-hand side from approximately the 125m mark, the elevation picks up quite dramatically. If one studies the orthophoto this is to be expected, as this is the area where the material still needs to be loaded out.

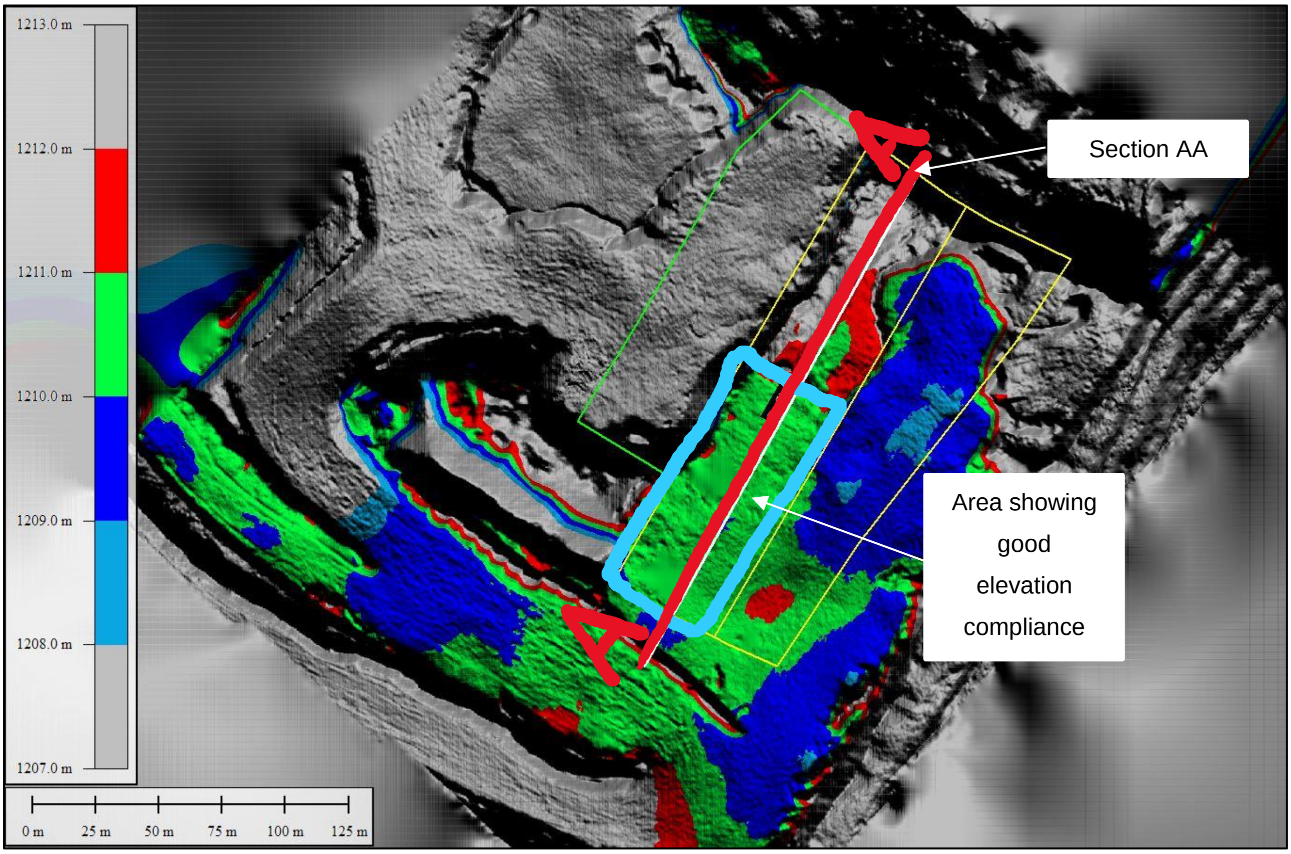

Figure 29: A view of the block depicting variation in elevation.

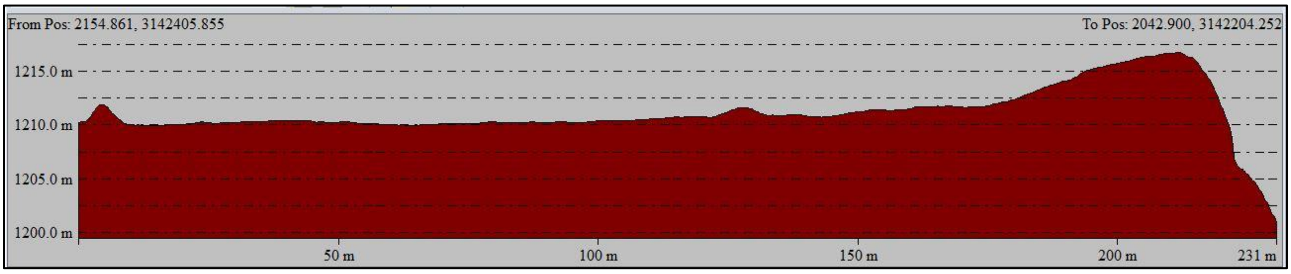

Figure 30: Section AA through the planned drill block.

In summary the block preparation has been reasonably well performed, given that the area where the drills will operate is well cleaned and on elevation. There is, however, some concern that a lot of the material adjacent to the block still needs to be loaded out and almost half the originally planned block has not been cleaned. It would have been better practice to have cleaned the whole of the originally planned block.

4.2 Drilling

The outputs that were envisaged as part of the objectives related to drilling activities can be seen in Table 4. The block identified for tracking of drilling activities was LFP0914O107, the same block that was focussed on for cleaning.

Table 4: Details for data related to drilling activities

Block Lifecycle Activity	**Data Collection and Processing**	**Envisaged Output**
Drilling	Use RPAS to collect aerial photos that can be used to create an orthophoto.	An orthophoto that can be used to monitor the drilling progress on a block. A means to compare planned versus actual hole positions.
Drilling	Use the orthophoto to create a point cloud and subsequently a DTM (digital terrain model).	A DTM (digital terrain model) that can be used to determine the position of the crest in relation to the first row of drill holes.

Once data pertaining to drilling activities had been processed, results as depicted in Figure 31, 32 and 33 were typically available. These three orthophotos show the progress of drilling activities over the course of a few days. Technically one could get an orthophoto for every day, but in this case only a few have been used to demonstrate that drilling activities can easily be tracked. By comparing the three images' progress in drilling, activities on the block could easily be interpreted. Figure 31 shows a view of the block when drilling has just commenced. It can be seen that two drill rigs have commenced drilling activities on the block. Figure 32 shows a view of the block where drilling is approximately halfway. It can also be seen that the loading of the block adjacent to the drill block is taking place. This is important, as it will have an impact on the result of the blast; the loading of this material determines whether there is a good free face. Another important observation is that the block seems to have been reduced or "cut" from the originally planned size. It appears from the image that the block is only half its originally planned size. Figure 33 shows a view of the block where drilling activities are almost complete. It shows only one drill rig on the block with a few holes still to be drilled. It also shows that charging activities have started taking place, as three MMU's (Mobile Manufacturing Units) can be seen on the block. These units are used to dispense bulk explosives into the drilled holes. A concerning observation is that there is no longer loading equipment adjacent to the block (as shown by the red area outlined in the photo). This type of imagery may also be helpful regarding aspects related to safety, such as the proximity of drilling to charging activities.

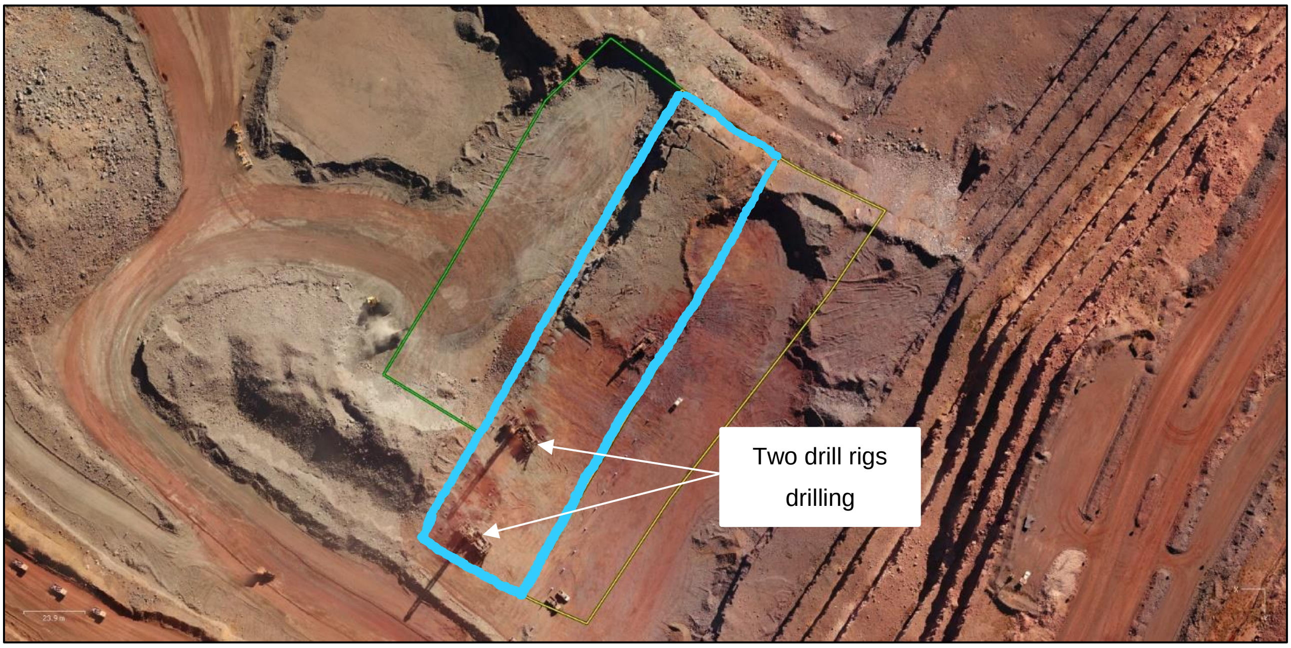

Figure 31: A view of the block when drilling has just commenced on 23 May 2018.

Figure 32: The block when drilling activities are approximately halfway on 24 May 2018.

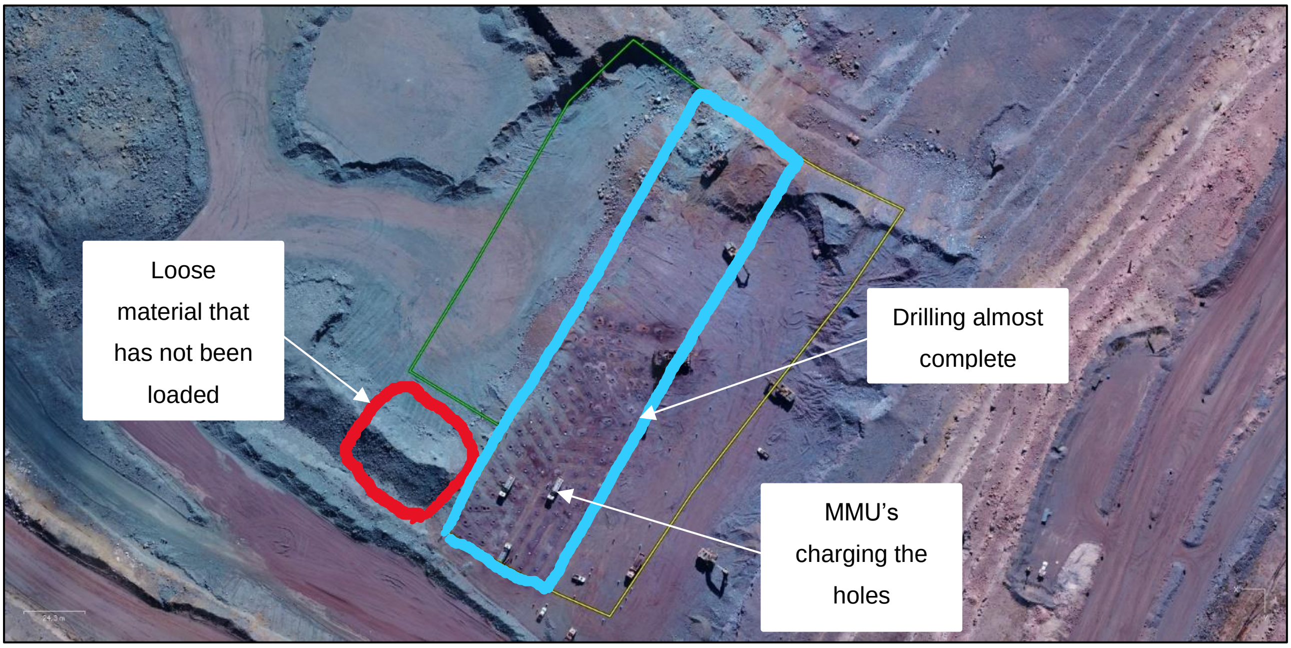

Figure 33: The block when drilling activities are almost complete on 29 May 2018.

By plotting the planned hole positions on the orthophoto, one can get a sense of the quality of the drilling. This is shown in figure 34. The white dots in the orthophoto indicate the planned drill hole positions. In this particular image it is quite difficult to see the actual drill hole positions, due to the image in the document being quite small. However, figure 35 shows a view where the software has been used to focus in on a particular portion of the block. The resolution in this instance is far better, and one can more easily distinguish between planned and actual drill holes. It should be noted that this block was drilled by two of the mines autonomous drills. This means that a significant amount of information pertaining to drill activities would have been available to management. However, if this block had been drilled by a contractor, no information pertaining to spatial (x,y coordinate) compliance would have been available. From figure 34 it is clear that the block was cut from its original size, as there are planned holes where there are no drilled holes. This is shown by the red area outlined in the photo. Figure 35 shows a close-up view of the block and depicts relatively good compliance in terms of planned vs actual hole positions. The area outlined in yellow shows a few holes where planned versus actual positions differ markedly. The area outlined in red shows a few additional holes that do not appear to have been planned. Another concern is the distance of the front row of holes to the crest. The crest is difficult to distinguish, as not all of the material has been loaded out in front of the face. This type of information could also be used by the mine's survey department to map the position of holes drilled by contractors. This would mean less time in the field mapping manually.

Figure 34: A view of the block showing planned versus actual drill hole positions.

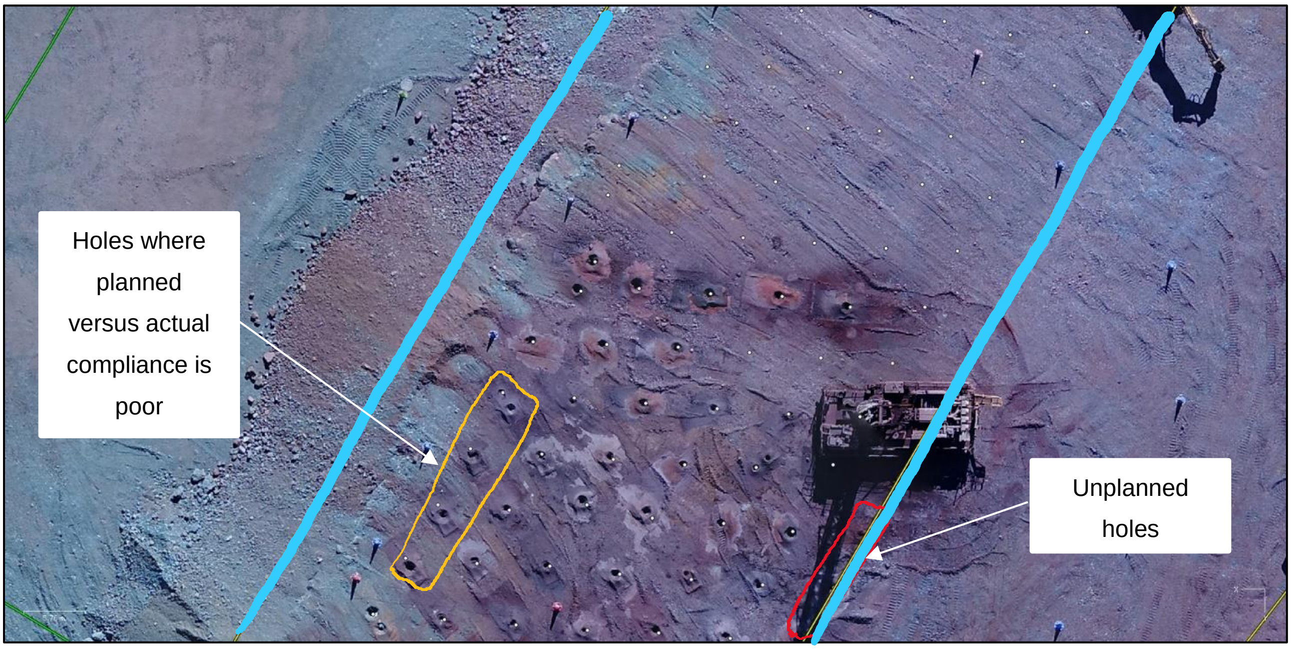

Figure 35: A focussed view of the block showing planned versus actual drill hole positions.

Views that can be obtained by using a combination of the DTM and the orthophoto can be seen in figure 36 and 37. Figure 36 shows a view of the DTM, depicted in green, where the crest has been drawn in red. The white dots represent the planned drill hole positions. Figure 37 shows a more useful view where the orthophoto has been draped over the DTM. This allows a view of the crest (shown in red), the planned hole positions, as well as the actual hole positions. Of interest is the distance of the first row of drill holes to the crest. This will bear significant impact on factors like stemming ejection and flyrock when the blast takes place. It will ultimately make a significant contribution to the success of the blast in terms of fragmentation. The rule-of-thumb is that the first row of drill holes should be equal to half the burden. The burden is the distance between the rows of drill holes. It is depicted by the light blue arrow in the image. The area outlined in green indicates where holes are overburdened. In this case, four drill holes in the first row are blocked by excess material, indicating a risk of choking in this portion of the block. Because there is a lot of material in front of the block that has not been loaded out, the area outlined in pink also suggests a concerning presence of overburdened holes.

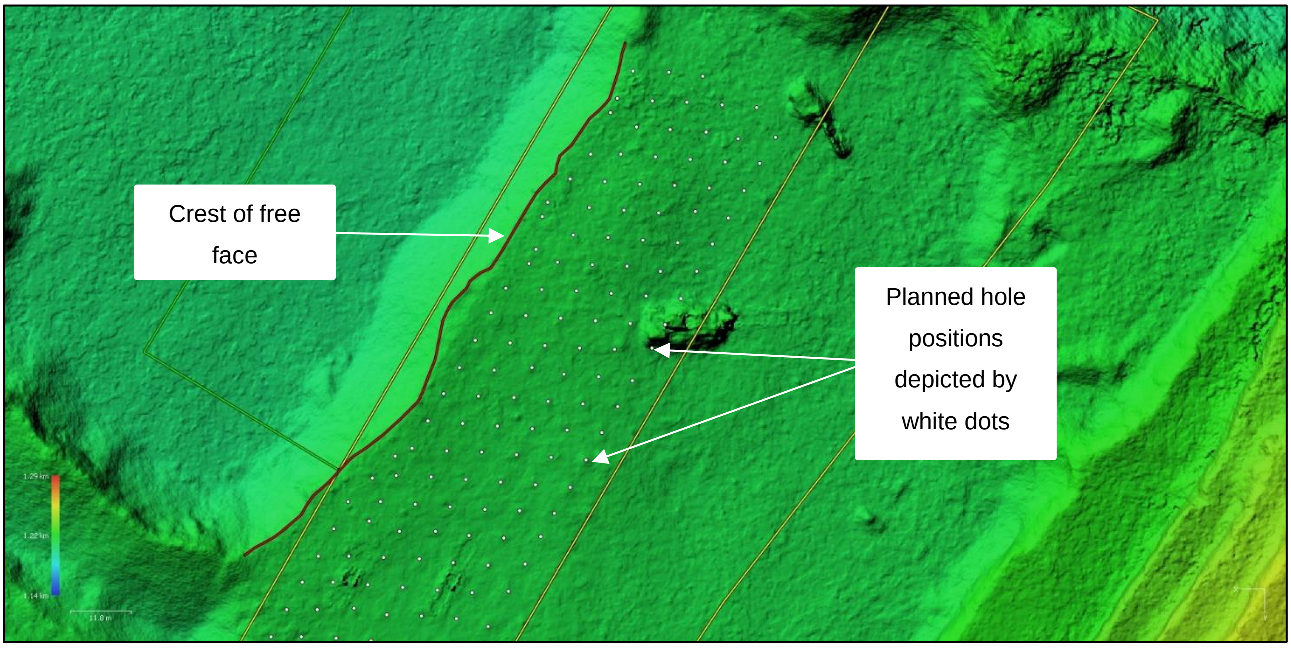

Figure 36: A view of the crest of the drill block and planned drill hole positions.

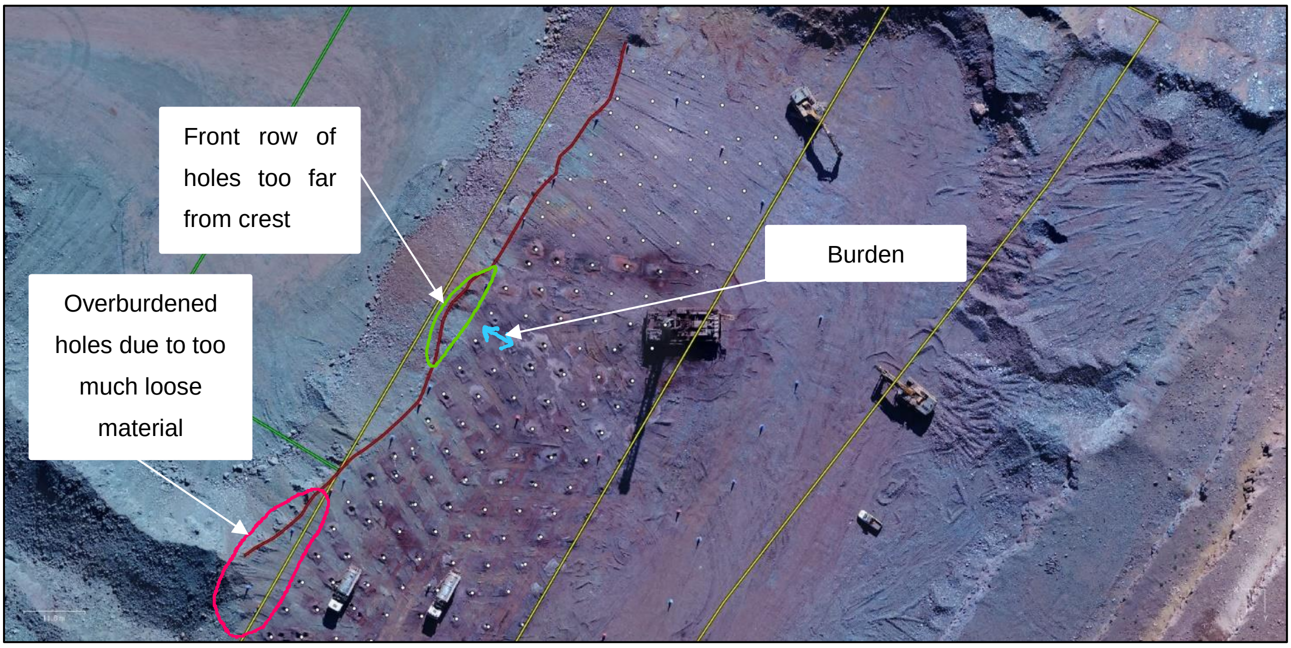

Figure 37: A view of the crest with planned and actual hole positions on the orthophoto.

In summary the drilling of the block has been reasonably well performed with relatively good compliance between planned and actual hole positions. This is to be expected, considering that drilling was performed by autonomous drill rigs. There are, however, some concerns around the number of holes in the first row of drill holes that appear to be overburdened. This could result in chocking of the face when blasting occurs and may even result in some poor fragmentation in the block. Another significant concern is the blasted material adjacent to the block which has not been loaded out. This will certainly constrain the block when blasting activities take place and could also result in sub optimal fragmentation.

4.3 Charging and Blasting

The outputs that were envisaged as part of the objectives related to charging and blasting activities can be seen in Table 5. The block identified for tracking of charging and blasting activities was LFP0914O107, the same block that was focussed on for cleaning and drilling. The block identified for fragmentation analysis was LFP1114O111.

Table 5: Details for data related to charging and blasting

Block Lifecycle Activity	Data Collection and Processing	Envisaged Output
Charging and Blasting (Pre-Blast)	Use RPAS to collect aerial photos that can be used to create an orthophoto.	An orthophoto that can be used to check whether material adjacent to the block has been loaded out, in order to expose the free face/s.
Charging and Blasting (During the blast)	A video of the blast.	A visual means to confirm that the blast area has been cleared of personnel and equipment. A visual means to assess the blast in terms of the firing sequence of holes, flyrock, dust and fumes.
Charging and Blasting (Post-blast)	Use RPAS to collect aerial photos that can be used to create an orthophoto.	An orthophoto that can be used to visually assess aspects such as face movement, muckpile shape, flyrock and backbreak (damage to the crest) and fragmentation. A source that can be used as an input into image analysis software for fragmentation analysis.
Charging and Blasting (Post-blast)	Use the orthophoto to create a point cloud and subsequently a DTM (digital terrain model).	A DTM (digital terrain model) that can be used to assess aspects such as face movement, muckpile shape and backbreak (damage to the crest).

Once data pertaining to charging and blasting activities had been processed, results in the form of orthophotos, DTMs and video footage were available. Figure 38 is an orthophoto of the block on the day that blasting took place. The photo clearly shows that all equipment has been removed from the block. Charging of the block had been completed and the block was ready to be blasted. Of concern was the material depicted by the area outlined in red, as its constrained movement would impact the effectiveness of the blast at the front of the block. The RPAS was used to assist the blast clearance process by ensuring that people and equipment were not in the vicinity of the blast. The RPAS pilot and foreman had a live view and verified that the area was clear and ready to be blasted.

Figure 38: A view of the block on the day of blasting on 31 May 2018.

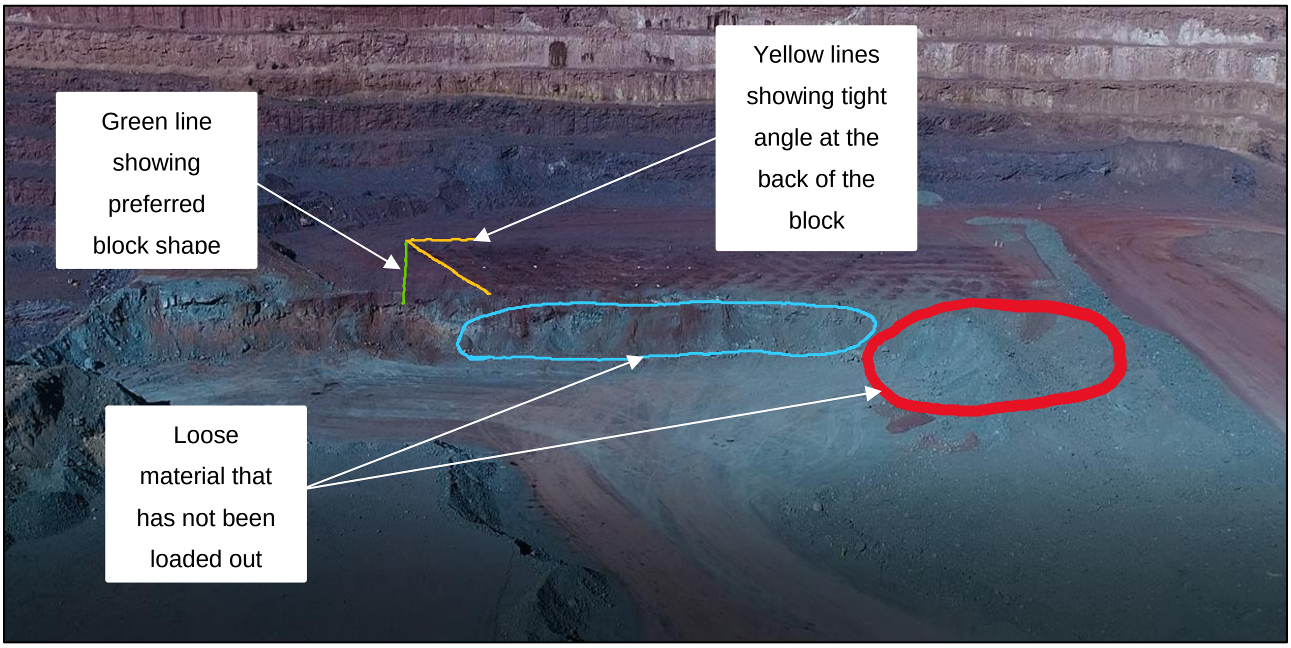

Figure 39: The block prior to blasting obtained from video footage.

Figure 39 shows a view of the block that was captured when taking a snapshot from the video of the block prior to blasting. There are a few areas of concern. As previously discussed, the area outlined in red shows material that should have been loaded out prior to blasting. Secondly, the area outlined in light blue shows other material in front of the face that should have been loaded out. Lastly, the lines drawn in yellow show that the drill holes at the back of the block may have been constrained, as the angle at the back of the block was tight. It would have been preferable to have the angle closer to 90 degrees, as shown by the line in green.

When the block was initiated the RPAS was positioned approximately 180m away from the blast. Although the video cannot be inserted into this document a few snapshots have been combined to provide a view of the blast. Figure 40 includes four images which contain some important information pertaining to the outcomes of the blast. Image 1 captures the block at the time when some of the first holes were detonated. As predicted, the material that was not loaded out in front of the block prior to the blast had impacted the blast. The plumes of dust emitted from four holes further back in the block indicates that the face had not yet started moving. The energy was evidently constrained in the block, and the route of least resistance was for the stemming material to eject from the drill holes. This means that the energy was dissipating vertically/upwards and out of the holes, instead of dissipating horizontally into the surrounding rock mass. Image 2 shows a view a few milliseconds later. It can be seen that the face had still not started moving and that a significant number of holes had blasted in an upwards direction. Another aspect worth considering is that a number of the holes in the first row were overburdened; this may have also impacted movement of the face. Image 3 shows where the face starts to move, as material can be seen moving at the front of the block. Image 4 shows a view of the blast from a location that is further back. What is important to note in this image is the amount of flyrock in the image. This is yet another indication that the block was constrained by the material that was not loaded out before the blast.

Once the blast had taken place, and the re-entry period had passed, the team could return to the block to view the outcomes. A second video was made of the recently blasted block in order to assist with some qualitative analysis. Figure 41 and figure 42 show two snapshot views of the muckpile from different vantage points. Figure 41 shows that the fragmentation of visible material looks acceptable. There does not appear to be an excessive amount of oversized material present. However, it should be noted that in the two areas outlined in red there is some coarse material. This coarse fragmentation has resulted in areas where the block was constrained during blasting (See figure 39).

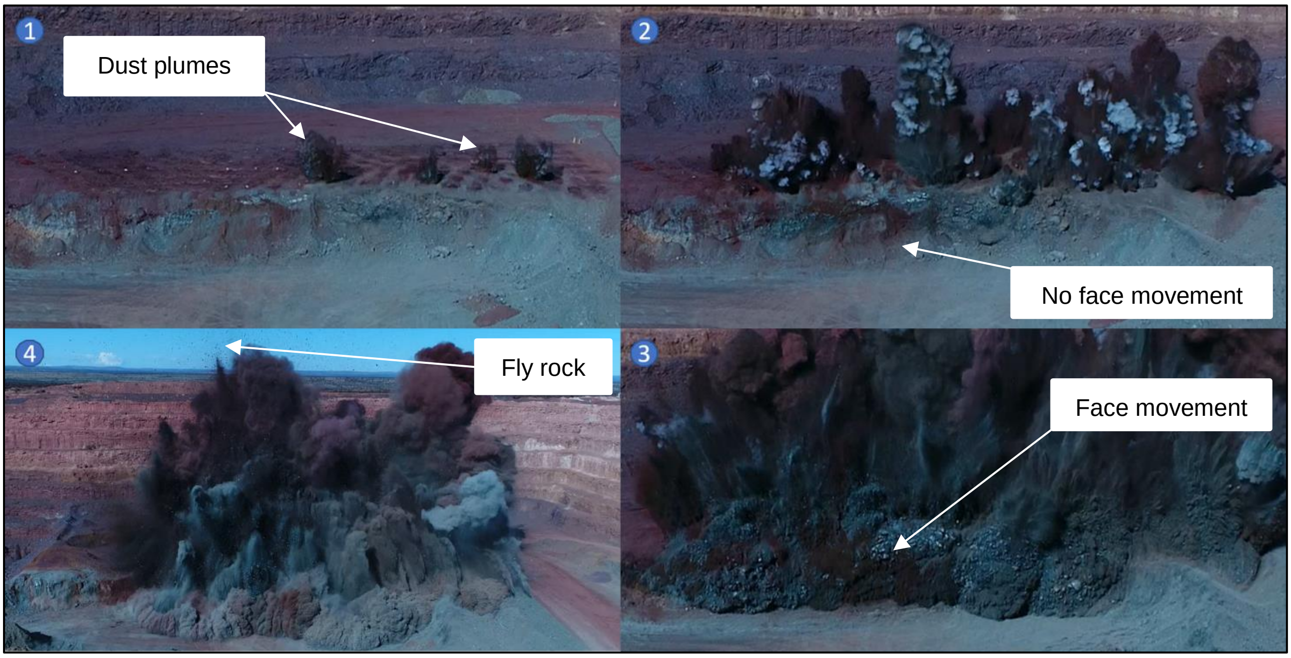

Figure 40: A sequence of snapshots showing the progress of the blast being initiated.

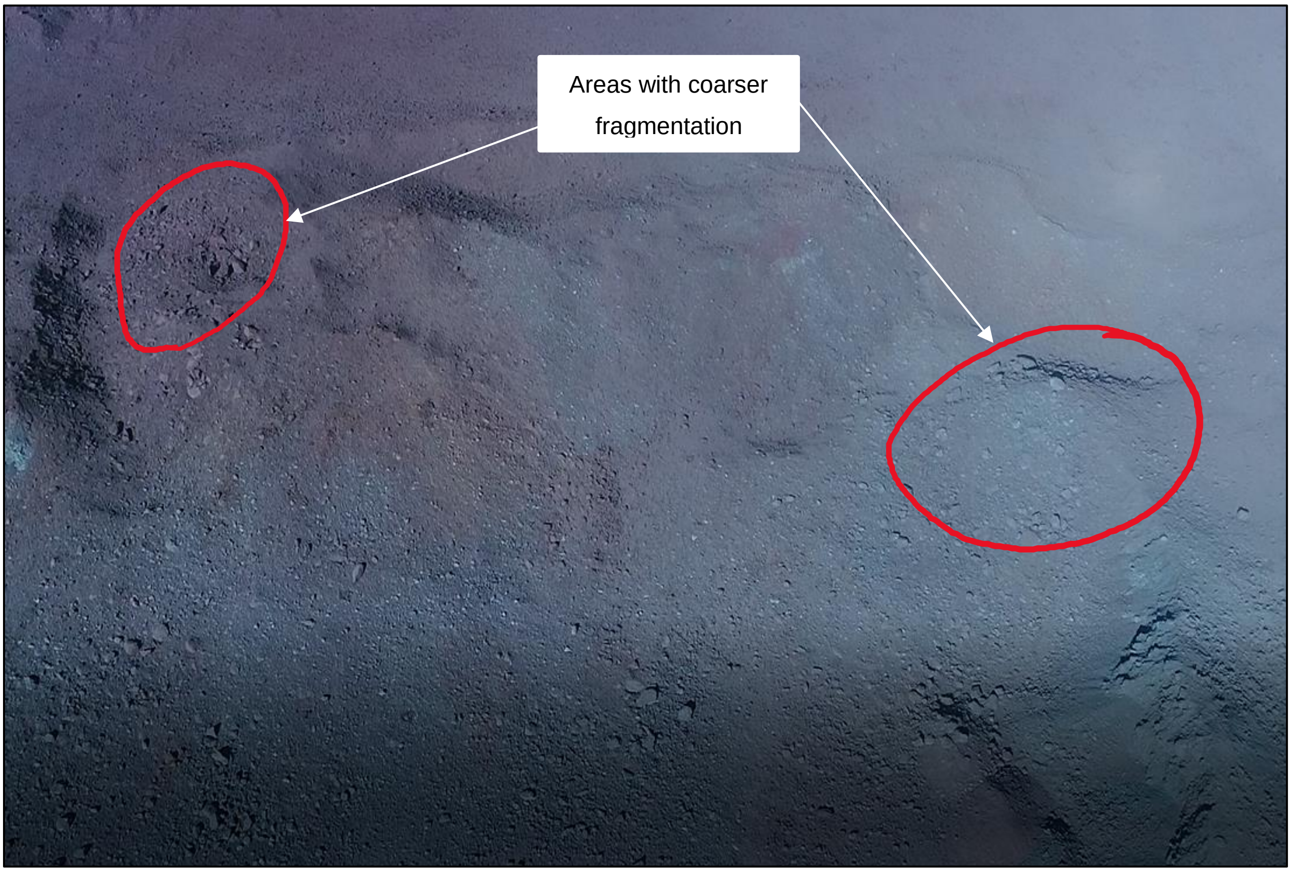

Figure 41: A view of the muckpile after blasting.

Figure 42 shows a view from the side of the block. From this it can be seen that there is a power trough at the back of the block. The power trough is indicated by the area outlined in yellow. Normally one would like a deeper power trough with a sharper angle to show that the block has been cleanly cut at the back. The green line shows from where clean-up activities would need to commence. The muckpile shape is quite flat, which means that a lot of time would need to be spent by a dozer and grader cleaning the area and preparing the block for loading. One can also get a sense of the amount of flyrock, which in this case is a significant factor.

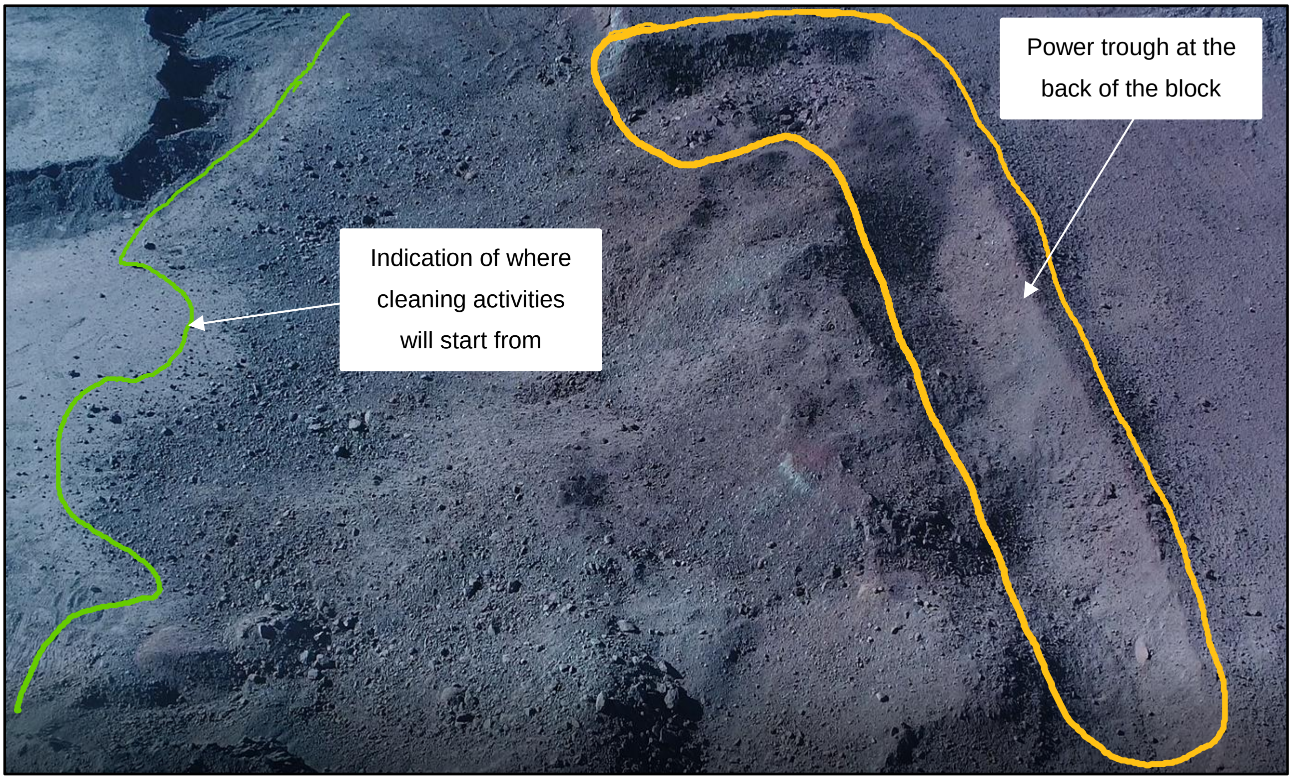

Figure 42: A view of the muckpile showing the muckpile shape and power trough.

Figure 43 shows an orthophoto of the blasted material that was taken a few days after the blast. The block stood for quite some time before loading activities commenced. One can see from the image that the material that was in front of the block after the blast has been cleaned, as well as the block, were ready for loading. The flat shape of the muckpile may mean that a front end loader should have performed loading initially until such point that there was sufficient face height to allow for a larger shovel.

Figure 43: An orthophoto of the block a few days after the blast on 5 June 2018.

One of the main objectives of the study was to determine whether quantitative fragmentation assessments could be performed using RPAS data. Throughout the duration of the assessment, new learnings were acquired, which in turn informed new adaptations to the fragmentation analysis using data collected by the RPAS.

Initially data was collected to compare the traditional fragmentation analysis method with the RPAS methodology. This exercise was performed in conjunction with staff from the Blast Consult & Explosives Effectiveness division of Sasol. Sasol staff collected data by taking a number of photographs using a high resolution digital camera and small soccer balls as reference objects. This represented the traditional method whereby reference objects are placed on the blasted material in order to assist with scaling when the images are processed. Figure 44 shows an example of an image acquired using the traditional camera method. Each time the two balls were placed on the blasted material and a photo was taken by the Sasol representative the RPAS pilot would hover the craft above the same location and take a photograph using the RPAS. The RPAS pilot essentially mimicked the traditional method. Figure 45 shows an example of an image acquired using the RPAS.

Figure 44: Photograph taken by traditional camera method showing two reference objects.

Figure 45: Photograph taken by the RPAS showing two reference objects.

Once the data had been collected, it was processed by the Sasol team, using the Split-Desktop® image analysis software package. Thereafter a report detailing the results was compiled and distributed. Figure 46 shows the size distribution curves that were obtained based on the two methods. As can be seen, there are differences in the shapes of the two curves in respect to the sizing of particles interpreted by the software. This difference is more pronounced for the smaller sized particles which are at the bottom of the two graphs. Figure 47 shows a more detailed breakdown of the sizing data. Again, the differences in the sizing is apparent.

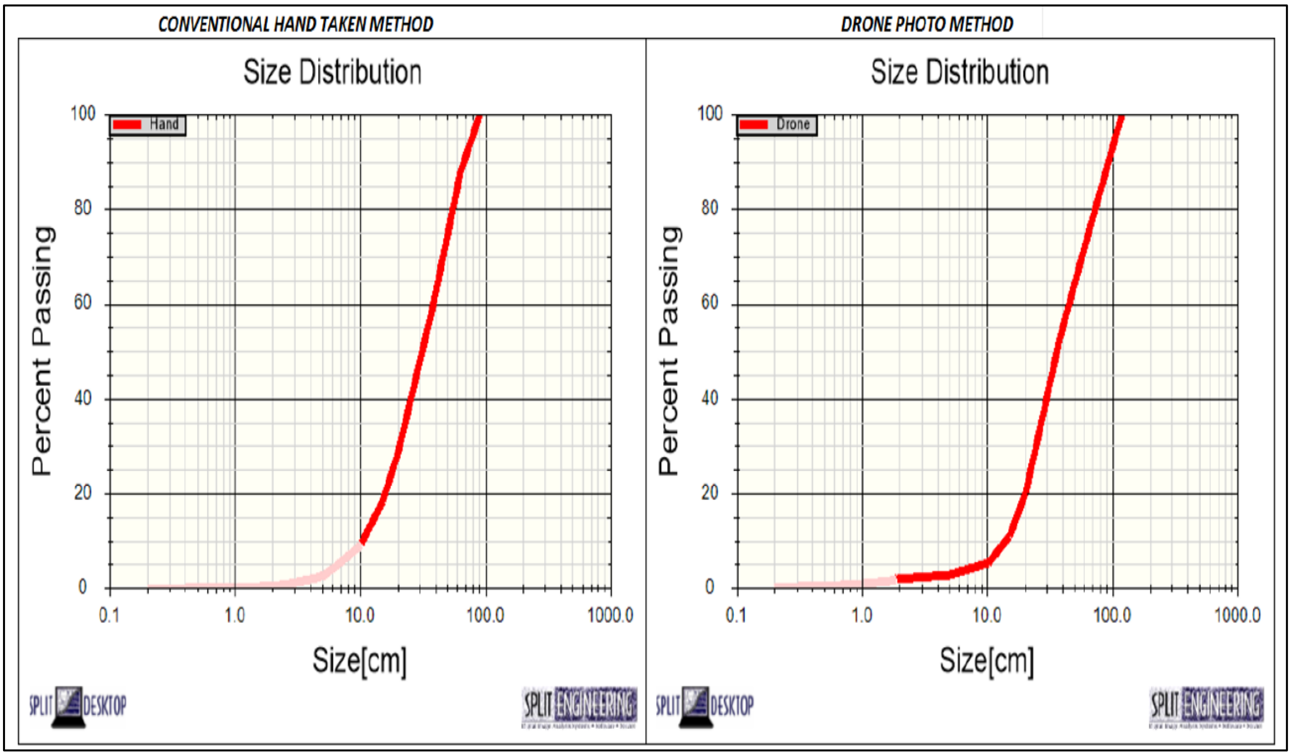

Figure 46: Size distribution curves for the traditional and RPAS methods.

	Hand	Drone
% Passing	Size[cm]	Size[cm]
P10	10.64	14.52
P20	16.06	20.21
P30	20.79	24.85
P40	25.72	29.79
P50	31.54	35.84
P60	38.49	45.12
P70	46.42	57.64
P80	54.9	72.04
P90	66.45	87.86
Topsize (99.95%)	91.28	120.01

Figure 47: A size distribution table for the traditional and RPAS methods.

In the Sasol report it was stated that, on average, the two methods differed by 26%. Reasons for the differences were not discussed. One could conclude that there was not a definite means of determining whether one analysis technique was better than the other. There are a number of possible explanations as to why the results were different for the two methods. These include, but are not limited to, the following:

- The cameras that were used to take the photos were different. The camera specifications were different.
- The angle at which the photos were taken was different for each method. This impacted the shadows on the images.
- The area that was photographed in each photograph was different. The traditional method had a more focused view, whereas the RPAS method had a broader view because it was further away. This meant that the RPAS method, as opposed to the traditional method, was effectively seeing more of the muckpile.

In addition to receiving differing results, the methodology for capturing data seemed to be counterintuitive, given that the RPAS pilot was attempting merely to mimic the traditional method. Practically, this would not be of significant value because the effort involved in collecting the data was substantial: the RPAS pilot had to manually fly the craft and manoeuvre it in order to capture the reference objects on the blasted material within the RPAS camera's frame of reference. This would have taken a substantial amount of time and compromised the level of efficiency and safety associated with the task of data collection.

Based on the results obtained with the initial trial it was decided that a different approach had to be considered. Available literature suggested that a different software package for image analysis, namely WipFrag, could be used. The reason for this was that WipFrag is able to process orthophotos produced from RPAS data. (It must be noted that an orthophoto was one of the standard outputs of all the RPAS flights that were conducted for the purpose of this study. The other output was a Digital Terrain Model (DTM).)

Originally the intention was to use the orthophoto for the block that had been photographed for the initial fragmentation assessment purposes, namely LFP0914O107. However, a closer analysis of the orthophoto indicated that the resolution of the image was not suitable. The height at which the flight was conducted was between 150m and 160m. A decision was taken to use another block, namely LFP1114O111, for further data collection and analysis. On the day that block LFP1114O111 was blasted, a number of flights were undertaken at different heights. The intention was to determine whether the change in height would have an impact on the resulting size distribution generated by the fragmentation analysis software.

Figure 48 shows the orthophotos for the three flights that were conducted using the DJI Phantom 4 Pro unit fitted with a 20 megapixel camera. These images have also been included in a larger format in Appendix 4, 5 and 6. The flying heights were 120m, 80m and 40m respectively. It must be noted that the flights were undertaken in the late afternoon after the blast. This resulted in a variance of shadows among the images. However, when the processing of the images was performed in WipFrag, the areas where shadows appeared were excluded from the assessment. The data processing for fragmentation analysis was performed by staff from Micron Scientific (PTY) Ltd.

From a practical perspective, two aspects must be considered - namely data capture and data processing. With the second method, where the orthophoto was used for analysis, the data capture process was simplified and safer when compared with the initial trails done with Sasol. However, the time required to process data was significant. The orthophoto that was generated for the 120m flying height consisted of 54 images and took 4 minutes to process. The orthophoto that was generated for the 40m flying height consisted of 280 images and took 20 minutes to process. It must be noted that a high-end computer was used to perform this work.

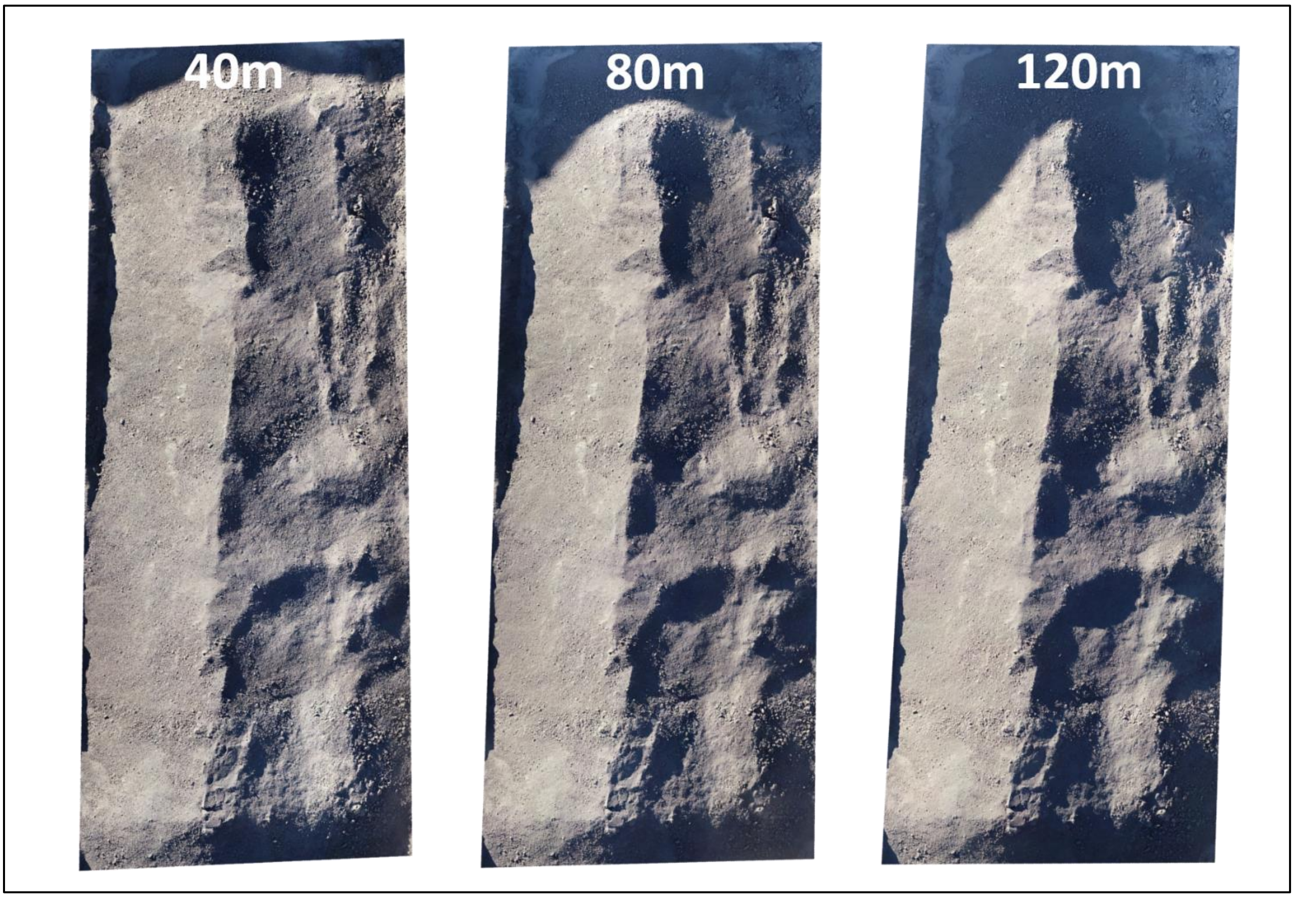

Figure 48: Three orthophotos that were used as inputs for fragmentation analysis.

As mentioned, processing of imagery was undertaken using the WipFrag image analysis software package. The software has the ability to process orthophotos, unlike Split-Desktop®. It easily managed to process the three images that ranged between 850MB (120m) and 3,5GB (40m). Figure 49 shows a snapshot of the WipFrag user interface. The image that is shown is the result of the initial image analysis where the software interprets the size of the particles in the orthophoto. This step is known as edge detection. The user has the ability to filter and clean up the image by closely assessing elements of the image such as shadows and concentrations of fine material. From the image it can be seen that in certain areas a large concentration of fines is interpreted as a large particle. If this is not removed from the analysis the result will be skewed. Although the software has a variety of settings and functions which allow the user to refine the analysis, a decision was made to keep the settings constant for the assessment of the three images. This was done to ensure a fair comparison of the three images. The overall processing time for each image was between 8 and 10 minutes.

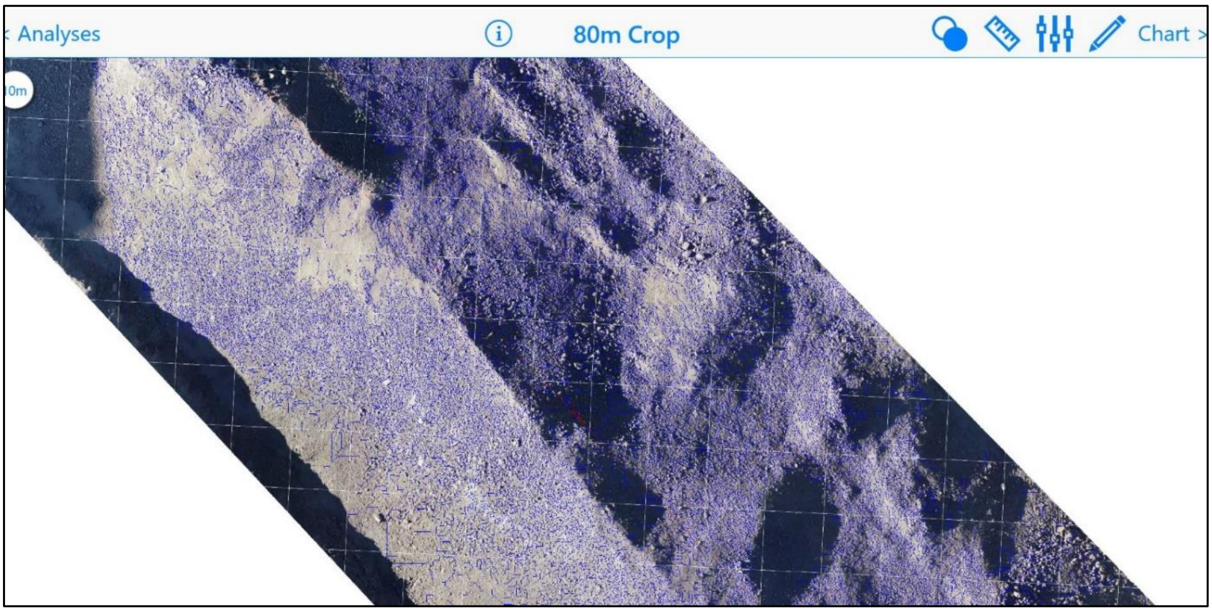

Figure 49: The WipFrag user interface.

The results of the image analysis can be seen in figure 50, 51 and 52. For ease of reference the results have been summarised in Table 6.

Table 6: Summary of fragmentation analysis results

Flying Height	40 m	80 m	120 m
Particles	161 804	51465	42 016
D01	147.12 mm	242.73 mm	256.08 mm
D20	352.01 mm	548.70 mm	591.66 mm
D50	577.91 mm	909.38 mm	998.69 mm
D80	1029.36 mm	2232.91 mm	2985.33 mm
D95	2710.86 mm	15181.89 mm	19695.32 mm

When comparing the three sets of results the following was found:

- The number of particles identified by the software increases significantly as the flying height decreases. The difference between the number of particles from 120m to 80m is approximately 22%. The difference between the number of particles from 80m to 40m is approximately 214%. This means that the image taken at 40m has 214% more particles than the image at 80m.
- The D01 result indicates the size at which 1% of the particles would pass through a sieve. For the orthophoto at a height of 120m, 1% of the material in the muckpile is smaller than or equal to 256.08mm. This result seems counterintuitive, as it means that only 1% of the material in the muckpile is smaller than or equal to 256.08mm. This is certainly not the case when one observes the 120m orthophoto, seeing as there is a lot of very fine material visible in the image. The difference between the D01 measurements from 120m to 80m is approximately 6%. The difference between the D01 measurements from 80m to 40m is 64%. By visually assessing the three orthophotos one would conclude that the image analysis software is inaccurate for the smaller/finer particle sizes.
- The D50 result indicates the size at which 50% of the particles would pass through a sieve. Practically, for the orthophoto at a height of 120m, this means that 50% of the material in the muckpile is smaller than or equal to 998.69mm. The difference between the D50 measurements from 120m to 80m is approximately 10%. The difference between the D50 measurements from 80m to 40m is 57%. Intuitively, when looking at the 40m orthophoto one would be more inclined to agree with the assessment that 50% of the material is equal to or smaller than 577.91mm.
- The D95 result indicates the size at which 95% of the particles would pass through a sieve. For the orthophoto at a height of 120m, 95% of the material in the muckpile is smaller than or equal to 19695.32mm. This result seems counterintuitive, as it means that there are particles in the muckpile that are larger than 19 metres. This is certainly not the case when one observes the 120m orthophoto. The difference between the D95 measurements from 120m to 80m is approximately 29%. The difference between the D95 measurements from 80m to 40m is 460%. By looking at the 40m orthophoto one would be more inclined to agree with the assessment that 95% of the material is equal to or smaller than 2710.86mm (2.7 metres).

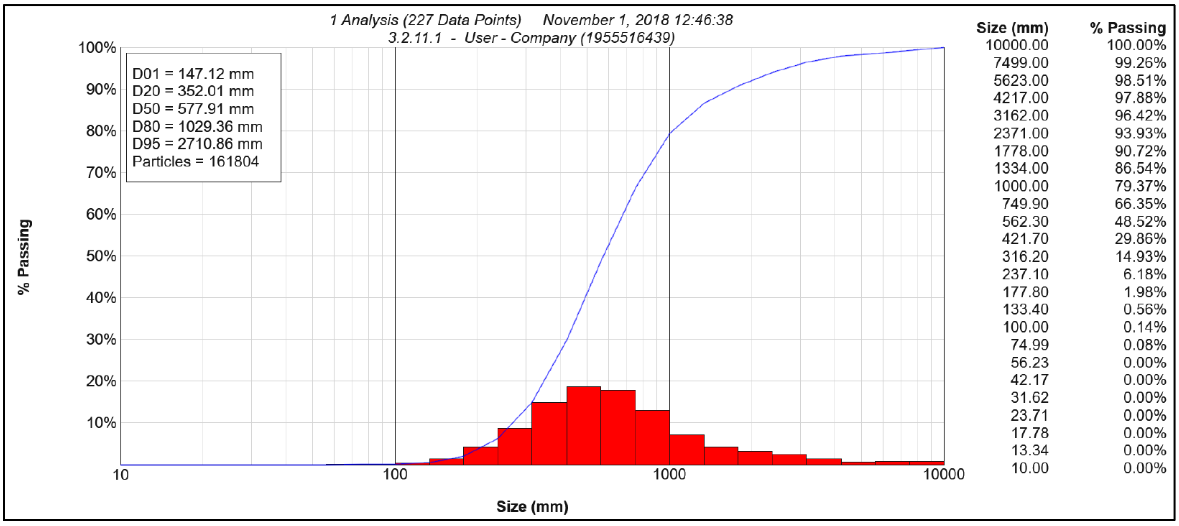

Figure 50: Fragmentation results for orthophoto at 40m.

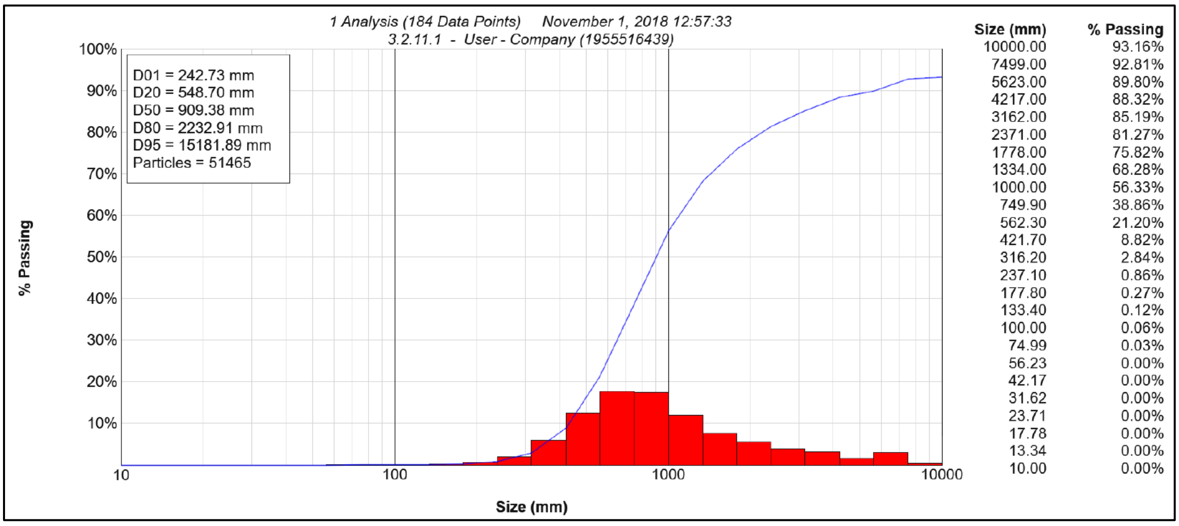

Figure 51: Fragmentation results for orthophoto at 80m.

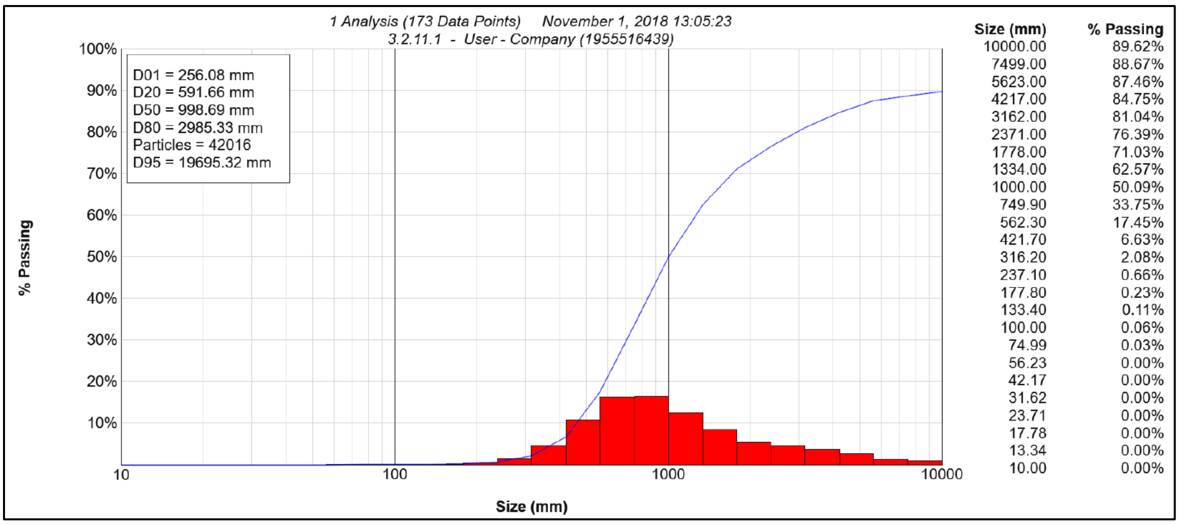

Figure 52: Fragmentation results for orthophoto at 120m.

Based on the results from the three size distribution diagrams it appears that a lower flying height results in a higher resolution orthophoto. This provides a more accurate size distribution analysis, because the software more accurately performs the analysis due to better particle recognition, i.e. it identifies more particles for assessment. The software seems to have limitations when identifying fine material - a conclusion that is echoed by other studies highlighted in the literature review portion of the document. The software also seems to struggle with the interpretation of large objects when the resolution of an image decreases. Logically this makes sense because the software struggles to identify individual particles and then ends up grouping a large number of particles together as one object.

4.4 Loading and Hauling

The outputs that were envisaged as part of the objectives related to loading and hauling activities can be seen in Table 7. The block identified for tracking of loading and hauling activities was LFP1114O111, the same block that was focussed on for fragmentation analysis.

Table 7: Details for data related to loading and hauling activities

Block Lifecycle Activity	Data Collection and Processing	Envisaged Output
Loading	Use RPAS to collect aerial photos that can be used to create an orthophoto.	An orthophoto that can be used to visually monitor the depletion of material within a blasted block.
Loading	Aerial photos to create a point cloud.	A DTM (digital terrain model) that can be used to measure volumes.

Once data pertaining to loading and hauling activities had been processed, results in the form of orthophotos and DTMs were available. Figure 53 and 54 show views of block LFP1114O111 after the blast. From the images it can be seen that the block was blasted as a box cut, as there are no free faces on the sides of the block.

Figure 53: Block LFP1114O111 after the blast.

Figure 54: A side view of block LFP1114O111 after the blast.

Figure 55 is an orthophoto of the block which clearly depicts the progress of loading activities. One can see that, due of the block being blasted as a box cut, the loading activities have ramped down into the block. From the image it appears that the fragmentation has not hindered loading activities. Due to the dust from the loading process, the specific loading equipment currently at use is difficult to distinguish. In a case like this one could search the raw photos for a shot which provides a clearer view. From a practical perspective the loading methodology or sequence of loading can be improved on. There is a lot of material on the periphery of the block which should have been loaded in order to open up the loading area. By loading out all of the material, the traffic flow on the block could have been improved and truck cycle times most likely could have been positively impacted.

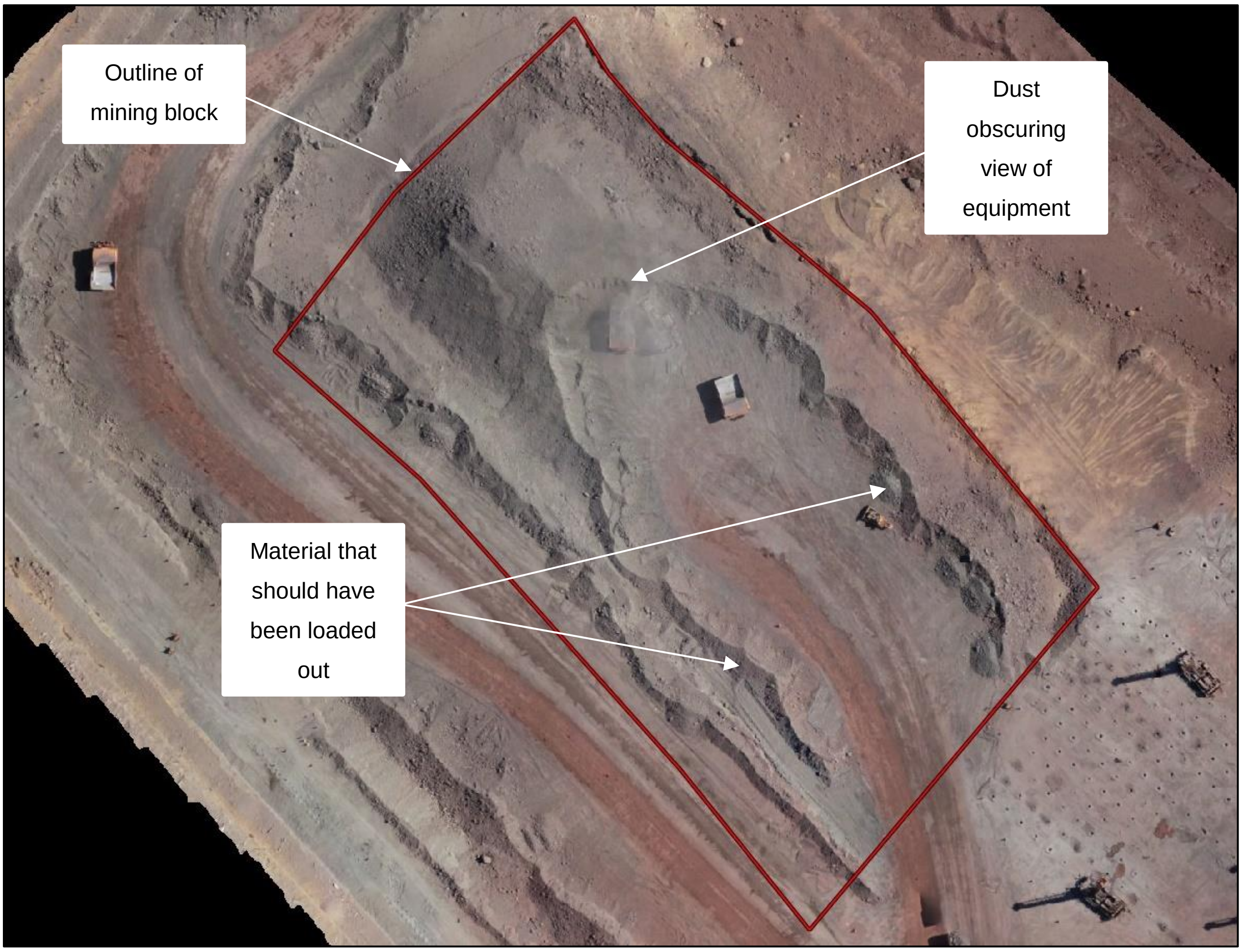

Figure 55: An orthophoto depicting progress of loading activities on 27 October 2018.

Figure 56 is another orthophoto of the block which again clearly indicates the progress of loading activities. Figure 57 shows a view of the block from a different vantage point. This view is generated by draping the orthophoto over the DTM. This view provides a better feel for the height of remaining material than the plan view in figure 56. How the data will be viewed and interpreted is at the discretion of the end user, as a variety of views are available once the orthophoto and DTM have been created. From figure 56 and 57 one can see that there is currently no loading taking place. This is due to the adjacent block being prepared for blasting. Of concern is that there appears to be a lot of loose material in front of the block prior to blasting, especially in the two corners of the block. Additionally, there is a lot of loadable material that is spread out across the block that should have been loaded as part of the loading process. The result is that this material is not suitable for a large piece of loading equipment; the loading rate will not be favourable due to the low height of the remaining material. Most likely a secondary loader such as a front end loader will need to be used for this purpose. This will result in more time taken to properly load out the area.

Figure 56: An orthophoto depicting further progress of loading activities on 9 November 2018.

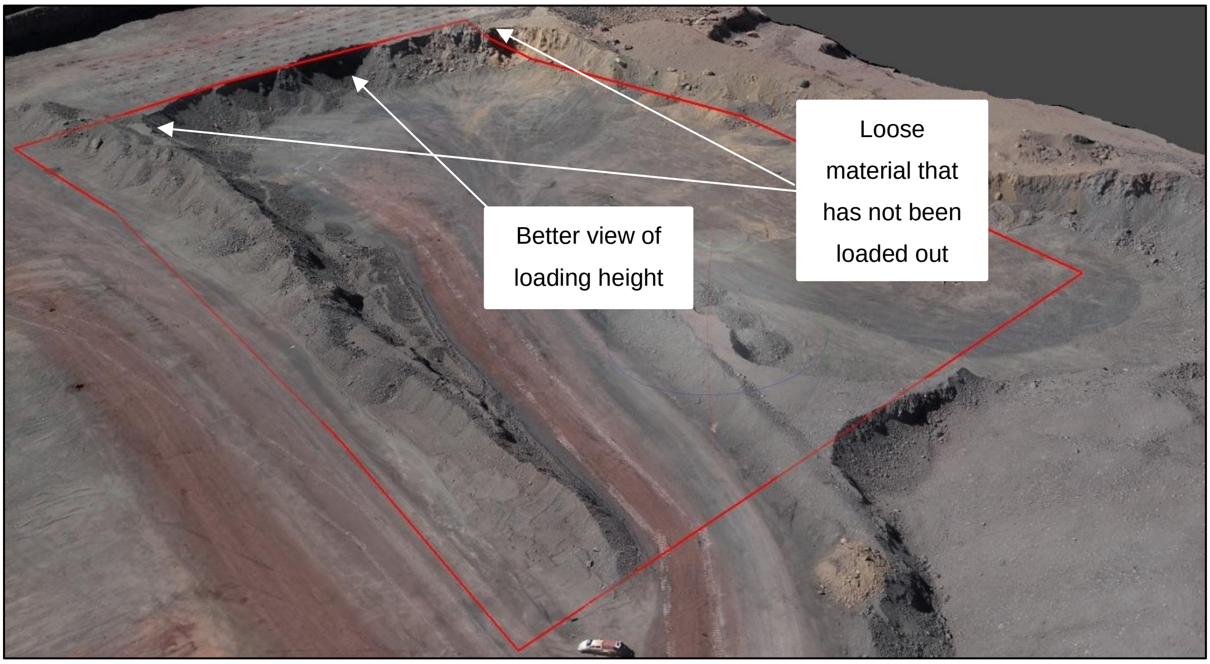

Figure 57: A view of the progress of loading activities from a different vantage point.

Figure 57 shows two DTMs that have been generated from the data. The DTMs have been loaded into the Global Mapper software package and show the loading progress on the 18th and 27th of October respectively. This software allows one to compare the difference in volumes between the two DTM. As a result, it is possible to calculate the total tonnage mined from the block. According to the mine planning department, the original tonnes associated with the block were 758 231t. According to the geological model, the density of the mined material was 2.66t/m^3. A swell factor of 1.25 was applicable after blasting. In this instance a volume difference of 99377m^3 was calculated. Therefore, a total of 211 474 tonnes has been mined thus far. Thus, the percentage of the block that has been mined is 28%.

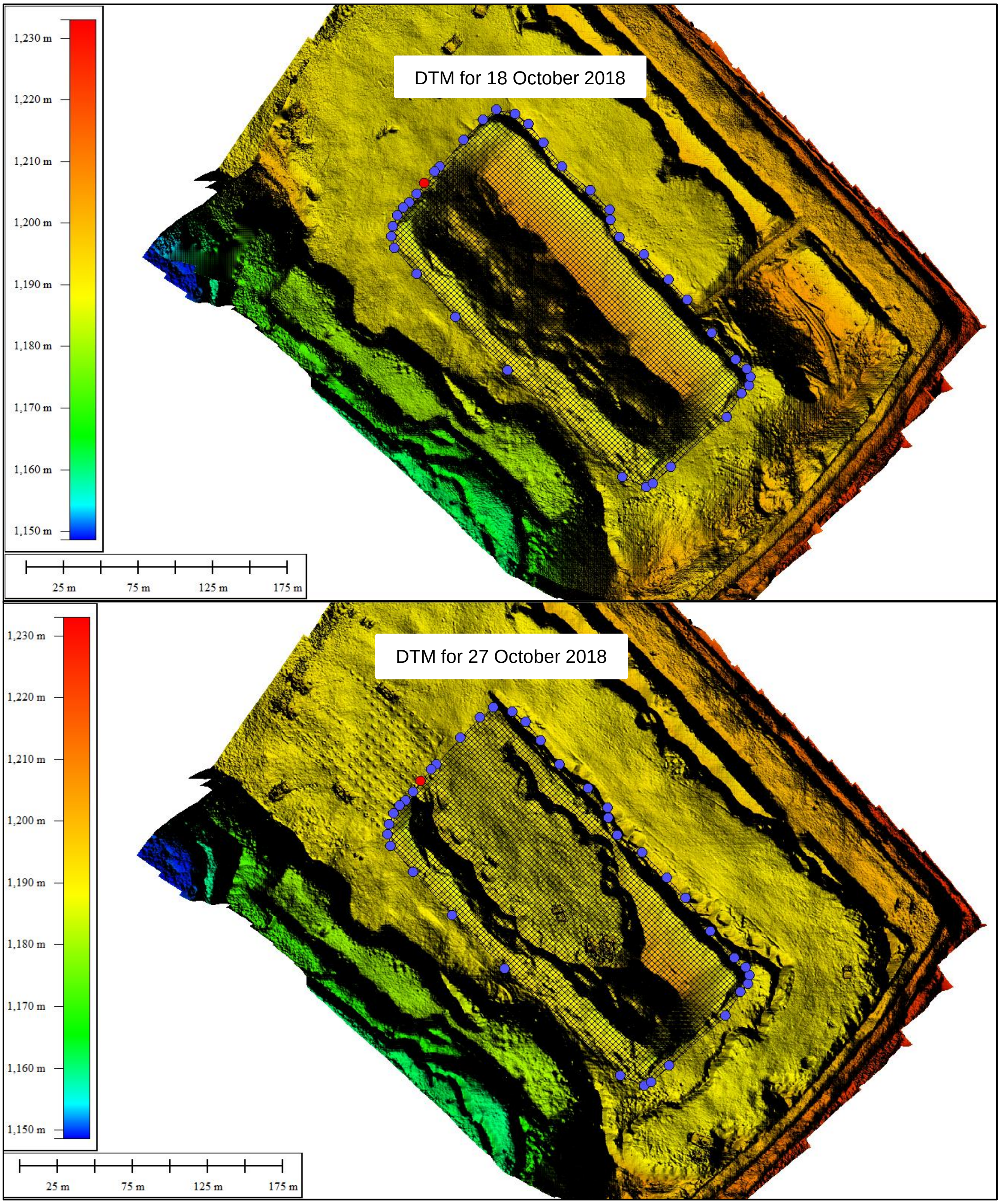

Figure 58: Two digital terrain models that were used to perform volume calculations.

5 CONCLUSIONS

This portion of the document aims to draw conclusions for each of the original objectives that were listed at the onset of the study.

Initially a comprehensive literature review was undertaken to:

- Introduce the topic of RPAS to create an understanding of the technology.
- Briefly outline the rules and regulations that govern the operation of RPAS technology within South Africa.
- Review how RPAS technology is being applied in the broader mining context.
- Focus on the application of RPAS technology within the mining production cycle. This focussed on the block lifecycle activities of cleaning, drilling, charging & blasting and loading & hauling.
- Review how RPAS technology has practically been used to collect data on other mining operations.

After the literature review, an "As-Is", or baseline assessment, was undertaken to collect information on methods that mine managers currently apply to monitor, manage and make decisions regarding block lifecycle activities. These activities include cleaning, drilling, charging & blasting and loading & hauling.

Once the baseline assessment was complete the data collection component of the study was undertaken. The aim of the data collection component was to determine how data, collected by means of an RPAS, could be converted into information that could be used for decision making by managers on the mine. The lifecycle activities that were assessed included cleaning, drilling, charging & blasting and loading & hauling. The data collection exercise was conducted using a DJI Phantom 4 Pro, fitted with a 20 megapixel camera. Data was subsequently processed in order to determine the kind of information, related to each of the block lifecycle activities, that could be made available to managers for decision making. This portion of the document aims to provide conclusions regarding the findings for the baseline assessment as well as the results from the data collection process. Additionally, a gap analysis has been conducted for each lifecycle activity.

5.1 Cleaning

5.1.1 Baseline Information

A manager has two main sources of information regarding block cleaning activities. The first is to receive verbal feedback from supervisors. There may in some cases be graphic content to verify observations that are communicated, such as photographs taken with a mobile phone or digital camera. The second option is for the manager to travel to the mining area to perform an inspection in person.

5.1.2 RPAS Information

Data collected by RPAS can provide high quality imagery in the form of an orthophoto that will allow a manager to monitor and validate progress of block preparation activities. The manager can verify whether the area to be drilled is clean and free of obstacles. Additionally, the DTM, generated as an output of the data processing, can provide an indication of the elevation of the block as well as the extent of undulations on the block.

5.1.3 Gap Analysis

In the case of cleaning activities RPAS can provide a step change in the amount of data and information that a manager has at their disposal. RPAS will provide the manager with information that was not available previously. This can assist the manager in ensuring that the first step in the block lifecycle is well tracked, managed and executed.

5.2 Drilling

5.2.1 Baseline Information

The amount of information that a manager has available on drilling activities depends on whether the drilling is being conducted by the mine's own drills or by a drilling contractor. In the case where drilling is being conducted by the mine's Caterpillar MD6450 autonomous drills, there is a vast amount of data available regarding both quantitative and qualitative aspects. In the autonomous drilling control room, the Flanders ARDVARC® system, which is fitted on the autonomous drill rigs, can provide details regarding drill location, machine performance metrics (rotational speed and pull down pressure), and machine health (oil temperature and air pressure). The operations control department can provide details related to drilling activities, such as equipment availability (%), equipment utilisation (%), actual metres drilled (m), average penetration rate (m/h), instantaneous penetration rate (m/h), Direct Operating Hours (DOH), machine delays and so on. Qualitative information related to drilling activities can be obtained from another system called BlastLogic.

BlastLogic allows for qualitative analysis by providing a view of drilling accuracy. Planned versus actual hole positions (x,y positioning), as well as planned versus actual hole depth, can be compared. When drilling is being conducted by one of the two contractors on the mine far less information is available. Quantitative information for contractor drilling will include a summary of metres per drill block and per pit. There is currently no qualitative information readily available regarding contractor drilling activities. In some cases the survey office will measure hole positions (x,y coordinates) for legal purposes, but this information is not widely shared. Contractor drilling activities account for approximately 20% of drilling at the mine. The manager also has the option of physically travelling to the mining area to observe the progress of drilling activities. This method has merit, in that the manager can gain a broader sense of context and insight into what is happening in the pit, particularly as it relates to safety.

5.2.2 RPAS Information

Data collected by RPAS can provide high quality imagery in the form of an orthophoto that will allow a manager to monitor and validate progress of drilling activities. Aspects related to safety can also be observed, such as the location of safety berms, as well as the proximity between charging and drilling activities, and so on. Drilling accuracy can be assessed by plotting planned hole positions on the orthophoto and comparing them to actual hole positions. A combination of the orthophoto and DTM can be used to indicate the location of the crest of the face in relation to the first row of drill holes. This can be used to get a sense of holes that are too close to the crest (under burdened) or too far away from the crest (overburdened).

5.2.3 Gap Analysis

Data collected by RPAS can provide managers on the mine with significantly more information related to contractor drilling activities than what is currently available. Both qualitative and quantitative information can be made available to promote better execution of drilling activities. This is vital, as it has a significant impact on the blasting and loading processes downstream. In the case of owner drilling, the RPAS has slightly less value to add, as there is a vast amount of information already availed to managers. However, several aspects can be tracked from the RPAS outputs and potentially add value to a manager, even when owner drilling is being done. The proximity of the first row of holes relative to the crest can be assessed. This is significant, since it has a major impact on the result of the blast. Similarly, the manager can check whether material adjacent to the block is being loaded out, as this also has a direct impact on the success of the blast. The manager can look at safety related aspects, such as whether drilling and charging activities are taking place on the block simultaneously, so as to ensure that these activities are not occurring in close proximity to one another. According to mine standards, the minimum distance permitted between drilling and charging activities is 15 metres. One could argue that the manager may only see this after the fact. Nevertheless, it allows for corrective actions to be implemented in order to avoid repeat occurrences. Lastly, the information related to the actual position of drill holes (for contractor drilling) will be able to be used by the survey department instead of having to go into the field to pick up hole positions (x,y coordinates) manually.

5.3 Charging and Blasting

5.3.1 Baseline Information

Currently data related to charging and blasting activities is not readily available to managers on the mine. Charging and blasting activities are managed by the blasting team, but this information is not available in the mine's control room. Some data and information are available in a software application called BlastLogic, which is in the process of being implemented. In the event that a video is made of a blast the manager may be able to get a copy of this to review. Additionally, the blasting team may take some photos to show the outcome of a blast in terms of fragmentation. The manager also has the option of going to the pit to observe charging and blasting activities. In the pit the manager can look at aspects such as cleaning in front of the free face, the number of holes yet to be charged, the progress of moving equipment for the blast (moving equipment out of the blast radius so that it is safe), confirming explosive densities with field staff, and so on. The manager may also choose to wait for the blast to take place in order to visually inspect the area afterwards where aspects such as fragmentation, muckpile shape and flyrock can be assessed.

5.3.2 RPAS Information

Data collected by RPAS can provide high quality imagery in the form of an orthophoto that will allow a manager to monitor and validate progress of charging and blasting activities. The progress of charging activities can be observed, as one can visually confirm where holes have been charged with explosives and stemming has been done. A high-resolution video can be made before, during and after the blast. For pre-blasting activities, a live video feed can be used for blast clearance monitoring (clearing of people and equipment from the blasting area) and for confirming whether all material in front of the free face has been loaded out. The video of the blast can be reviewed for insight into the blasting sequence (timing), ejection of stemming material from holes, face movement, dust and fly rock. The post-blast video and orthophoto can be used to assess aspects such as muckpile shape, fragmentation, backbreak and the presence of a power trough.

The orthophoto that is obtained from flying the block after the blast can be used for the purposes of fragmentation analysis. The fragmentation or size distribution of the blasted material is important to managers on the mine because it provides an indication of how well the material has been fragmented or broken up during the blast.

The following conclusions can be made based on the fragmentation analysis results in the previous chapter:

- The method of using an orthophoto for fragmentation analysis is a significant step forward (versus the traditional method where reference objects are used). The primary advantage is safety, due to the RPAS pilot not having to go near the muckpile in order to capture data (photos). The second advantage is that the orthophoto represents the entire block and not just a few small segments, as with the traditional method. This means that the result is more representative of the whole block. In this study the block used for fragmentation analysis was approximately 750 000 tonnes (a substantial tonnage), and the traditional fragmentation method may not have been representative, due to the small sample size principle applied.
- When collecting data with the RPAS the number of images increases significantly as the flying height decreases. This is because the field of view (what the camera can see) diminishes as the height decreases. This means that at a lower height more images are generated, and a longer processing time will result. The difference in the number of images when flying at 40m versus 120m was 519%. (In other words, there was a 519% increase in the number of images.) This had a significant impact on the processing time.
- The shadows on the mining block impacted the images. Ideally the images should have been acquired earlier in the day when the sun would have been more perpendicular to the pit.
- The fine material/dust that settled on the top of the block after the blast negatively impacted fragmentation results. In this case, the software appears to group patches of dust together as one large particle instead of delineating a large amount of small particles.
- For fine/small particles (particles less than 150mm in size) the image analysis appears inaccurate. This is primarily due to the software's inability to distinguish smaller particles.
- For medium sized particles (particles ranging between 150mm and 1000mm) the image analysis appears more accurate and realistic. The accuracy of the particle size distribution analysis appears to become more accurate as the flying height decreases. The orthophoto for a flying height of 40m yielded the most realistic result, when compared to the 80m and 120m flying height.
- For large particles (particles larger than 1000mm) the image analysis accuracy seems to differ significantly based on the flying height. It was apparent from the D95 results that the flying height of 120m yielded an inaccurate result of 19,7m, whereas the D95 results at 40m yielded a far more realistic result of 2710.86mm (2.7 metres).
- Data suggests that the flying height has a significant impact on the fragmentation analysis results. When flying lower the resolution of the orthophoto was found to be higher, which

allowed the software to perform better particle recognition, i.e. it identified more particles for assessment. The results for the 40m flying height appeared to be the most comprehensive and realistic when visually compared with the orthophoto.

5.3.3 Gap Analysis

By allowing managers to track charging progress visually, RPAS data can provide better insight than what is currently available for charging purposes. RPAS technology can significantly improve the amount of information that is typically availed to a manager regarding the blasting process. Every aspect of the blast, including safety, can be recorded in the form of aerial imagery and video footage. Even though the blast could be filmed in the past, the RPAS provides far more insight, because the block can be viewed from any location. The ability to process an orthophoto for fragmentation analysis is very significant. It provides a full comprehensive analysis of the muckpile (as opposed to a traditional camera method that analyses small portions of the muckpile). There is also a safety advantage when compared to the traditional fragmentation analysis method, which requires people to walk on the muckpile to place reference objects (normally soccer balls). By using RPAS, no person is required to walk on a blasted muckpile. When flying at different levels for fragmentation analysis, results indicate that a better outcome is generally achieved when the craft flies at lower elevations.

5.4 Loading and Hauling

5.4.1 Baseline Information

The level of insight into loading and hauling activities depends on who is conducting the activities. If loading and hauling activities are being conducted by the mine's own fleet, loading and hauling equipment is managed in a control room using a fleet management system called Modular Dispatch®. When in the control room, a manager can view the location of equipment, equipment performance, as well as the haul road network. Acting as the custodian of data and information to all mining activities, the operations control room provides readily available and quantitative information related to load and haul activities. These include: equipment availability (%), equipment utilisation (%), tonnes loaded (t), tempo (t/h), Direct Operating Hours (DOH), equipment delays and so on. The manager also has access to production performance summaries for the day, week, month or year. This will include planned (budgeted) versus actual numbers for aspects such as Expit ore, Expit waste, re-handled tonnes, movement between stockpiles, and so on.

Alternatively, loading and hauling activities can be conducted by a contractor. In such cases, far less information is available. The contractor equipment cannot be seen or tracked from the mine’s control room. Data pertaining to the performance of the load and haul contractor is communicated at a high level to the mine's operations control department for management reporting purposes. This typically includes a summary of the tonnes moved in a particular pit for the shift and for the day. A manager can also physically visit the pit in order to view the progress of load and haul activities. This provides context in terms of the conditions in the loading area, the volume of material yet to be loaded, the fragmentation, bucket fill factors and whether the block is being loaded correctly and in accordance with the mine standards. Safety related aspects, such as safety berms and the traffic management for the loading area, can also be confirmed.

5.4.2 RPAS Information

Data collected by RPAS can provide high quality imagery in the form of an orthophoto that will allow a manager to monitor and validate progress of load and haul activities. The imagery can be used to visually confirm how much of a blasted block has been loaded out and how much material remains. Additionally, the standards related to the loading sequence of a block can be confirmed. Such standards ensure that the block is loaded so that sufficient space allows for optimal entry and exit of haul trucks during loading. It also ensures that remnants of material will not be left behind, rendering additional loading at a later stage. DTMs generated by RPAS data can be used to perform volume calculations that in turn determine the tonnages that have been mined from a block.

5.4.3 Gap Analysis

Data collected by RPAS can provide managers on the mine with significantly more information related to contractor load and haul activities than what is currently available. Both qualitative and quantitative information can be made available, which promotes better execution of load and haul activities. Qualitative information will include the imagery that allows one to visually track loading progress, as well as the loading sequence and layout. Quantitative information will include the ability to determine volumes and hence tonnages that have been moved from a block. In the case of owner loading and hauling activities, the RPAS has less value add, given the vast amount of information already available to managers. However, the above mentioned qualitative information may also be of value to the manager, as it will provide good context when assessing quantitative data from fleet management systems. This can be a good tool to check the accuracy of fleet management systems.

5.5 Lessons Learnt

In addition to the aforementioned conclusions there were a number of lessons that were learnt during the process of the study. These learnings have been grouped into three categories, namely legal, technology and practical. Each will be discussed below.

5.5.1 Legal

Setting up to make legal use of RPAS technology for data collection on the mine in the Northern Cape proved extremely challenging. At the time Kumba did not have a license to operate its own units and there was a dependency on a contractor to assist. As with many research projects, there was also a challenge to fund the data collection process. Only a company with an ROC (RPAS Operating Certificate) and certified pilots and equipment were allowed to operate on the mine. The contractor was also required to provide a pilot, as well as equipment, for a lengthy period. In addition, the process was impacted by an Anglo American group safety rule that stipulated, any contractor operating RPAS technology on one of the mine sites must be BARS compliant. BARS refers to the Basic Aviation Risk Standard - a rigorous set of standards developed by the industry and contracting companies, based around the specific risks associated with daily aviation activities. Mainly, the challenges of BARS compliance are the cost involved as well as the time required. After almost 16 months, and two failed attempts to get a contracting company to site, there was success. A company called UDS (UAV & Drone Solutions (PTY) Ltd) indicated their willingness to assist in the research process and made available their time and resources to get the job done. They were one of the first companies in South Africa not only to have an ROC, but also to be BARS compliant. In May 2018 RPAS flights to collect data commenced.

There are also a number of other legislative requirements that must be fulfilled before RPAS operations can be undertaken on a site. This includes a comprehensive risk assessment and landowner's permission. In this case, one small advantage was that the location of the mine is quite remote.

5.5.2 Technology

The DJI Phantom 4 Pro was the RPAS platform selected to perform the data collection on site. This is a relatively cheap configuration with the RPAS unit, costing in the order of R30 000. Overall the unit performed well, and all the planned tasks could be executed with the Phantom 4 with a 20 megapixel standard camera. The camera had the ability to acquire still images, which were used in most cases, as well as video. There were two instances where a higher specification camera may have had an influence. The first instance was when fragmentation analysis was performed. It would have been good to test a few different cameras with varying specifications in order to determine the impact on fragmentation analysis results. It should be noted that the Phantom 4 camera cannot be removed or substituted. Therefore, if different specification cameras are to be tested in future, then a suitable RPAS unit will need to be selected. One good option is the DJI Matrice 210 or the DJI Matrice 600, which can carry multiple payloads. Secondly, a video camera with zoom capability would have been advantageous as a higher specification camera. The standard Phantom 4 camera does not have zoom capability. The ability to zoom would provide a better video of the blast when it is initiated and could be safer, because it allows the RPAS to hover further away from the blast. It has been mentioned that the Matrice 210 and Matrice 600 can carry multiple payloads, one being the DJI Zenmuse Z30 camera with 30 times zoom capability.

5.5.3 Practical

There were a significant number of practical site-based learnings during the course of the research project. For ease of reference the practical learnings will be discussed in a bulleted format.

- The process of getting people and equipment onto site can take a lot of time. Each site will differ, but in this instance the contractor was required to go through the full onboarding process of the mine. This process took about a month in total and included medicals, inductions, risks assessments and equipment clearance.
- Due to the rigorous requirements to bring a vehicle onto site and due to the relatively short duration of the research project a decision was made to make use of the mine's transport. The issue with this approach was that the team conducting the flying operations was very dependent on the availability of staff as well as the availability of a suitable vehicle.
- Before any flying could take place for the purposes of data collection the team had to identify the target area. The method of collecting the data is known as photogrammetry and this method requires ground control. The physical ground control were pieces of conveyor belt (400mm by 400mm) placed in and around the target area. Each GCP (ground control point) must be measured by the surveyor. Depending on the type of data and the required accuracy, the amount of ground control may differ. The result was that a great deal of time and effort was required to get ground control in place for each flight. In some cases GCP's that were placed on a given day would be disturbed by mining operations and would therefore be required to be resurveyed. It should be noted that there are now options available in terms of RPAS units that have PPK (Post Processed Kinematic) functionality. This means that the RPAS has a high precision GPS which allows one to do away with ground control. This will be a significant time-saver in future and will boost the ability to cover more areas in less time.
- The aspect of change management played an important role in the project, as people on the mine were not used to seeing RPAS's being operated. It was important to dispel any misconceptions regarding the purpose of the flying activities, as it was rumoured that many

people saw it as tool to monitor employee behaviour. By working closely with the mine's communication department, the correct message was conveyed to all stakeholders on the mine and no issues were encountered whilst conducting the research.

- In the Northern Cape the wind plays a role in the operation of RPAS. There were a few occasions where planned flights were postponed or cancelled due to excessive wind speeds. Each RPAS unit has a specification in terms of wind tolerance. The Phantom 4 Pro that was used in this instance can tolerate winds speeds of up to 10m/s. Excessive wind impacted about 5% of the planned flights.
- When conducting flights, the endurance (the amount of time for which a unit can fly), became important. The Phantom 4 was able to safely conduct a flight or mission for about 15 minutes. The general rule-of-thumb was that the pilot would bring the unit back when battery life remained at 40-50%. In most instances between 3 and 4 flights were required to cover the planned target area (on average about 1.2km^2). This process would take between 60 and 90 minutes. As battery technology improves the endurance of units will certainly increase, but for the time being limited endurance is an aspect of RPAS operations that cannot be ignored. This factor also bears cost implications, as several spare batteries and chargers are required.
- From a data perspective one must always consider the impact that the size of the target area will have on the subsequent data processing step. Logic dictates that the larger the area the higher the number of photographs that are taken - and hence the larger the data set. Flying higher can help reduce the number of photos, but there will be a compromise in resolution and accuracy. There is also a legal ceiling of 400ft (±120m), (1000ft (±300m), should SACCA exemption be obtained. In addition to the large volume of data requiring processing, the processing power available to the person conducting the data processing step will impact the process significantly. Processing of flight data for the purpose of generating an orthophoto and DTM on average took five and a half hours. The average number of photos was 1200 with the size of the raw files being in the order of 9GB. Processing was done using a computer with the following specifications:
    - Processor – Intel i7
    - CPU – 4.8GHz
    - Graphics – Two Nvidia 1070Ti 16GB graphics cards in crossfire
    - RAM - 32GB Hyper X High performance
- In the longer term one will also have to consider requirements in terms of storage space. One will very quickly end up with massive volumes of data that need to be stored.

6 RECOMMENDATIONS

This research study was focussed primarily on value that RPAS technology can add to the physical mining process in the form of the block life cycle activities of cleaning, drilling, charging & blasting and loading & hauling. The study yielded many instances where everyday decision making by managers can be improved through the use of data and information generated by RPAS technology. Practically, a mine may decide to pursue some recommendations whilst others may be less appealing. In providing recommendations the approach has been to group by block life cycle activity and then to provide more general inputs thereafter.

6.1 Cleaning

For the activity of cleaning the RPAS data and information will significantly impact the insight and decision-making capability of site staff. Managers will be able to easily track the progress of cleaning activities by means of an orthophoto of the mining block. Additionally, information pertaining to the elevation and the extent of undulations can be provided by analysing the digital terrain model. The mine may need to purchase a license for the Global Mapper software in order to perform this task.

6.2 Drilling

For the activity of drilling the RPAS data and information should be used to provide insight to both owner and contractor drilling activities. A combination of orthophotos and digital terrain models can be used. The proximity of the first row of holes to the crest of the face can be determined and analysed (this could not be done previously), and corrective actions can be implemented to fix deviations prior to the blast taking place. Orthophotos can be used to assess safety related aspects, such as the presence of safety berms and the proximity of drilling and charging activities to each other. Additionally, orthophotos can be used to ensure that material adjacent to the block, threatening to impact the blast, is loaded out prior to blasting. For contractor drilling, outputs from the RPAS can determine compliance in terms of planned versus actual hole positions, i.e. the quality of drilling. This information can also be used by the survey department to track actual hole positions for contractor drilling. This means that less time will be spent in the field manually measuring hole positions.

6.3 Charging and Blasting

For the activities of charging and blasting the RPAS data and information will have a significant impact on pre-blast, during blast and post blast insight. A combination of video footage and orthophotos will allow managers to know the exact state of the block prior to blasting. The charging process can be tracked, and blast clearance activities can be monitored. A video of the blast will provide the manager with insight into aspects such as the firing sequence (timing), stemming ejection, dust generation, and the extent of flyrock. After the blast a combination of orthophotos, digital terrain models and video footage can be used to assess aspects like face movement, muckpile shape, backbreak and fragmentation. The manager can also have the orthophotos processed using the WipFrag image analysis software application in order to get a formal interpretation of the fragmentation. The mine may need to invest in a license for the WipFrag so that analysis can be performed on site. More work will be required to determine an optimal flying height for fragmentation analysis.

6.4 Loading and Hauling

For the activities of loading and hauling RPAS data and information should supplement the current information that mine managers have about owner equipment fleets. This information would come as orthophotos, providing context to contractor loading and hauling activities, such as traffic management and spatial loading. Through orthophotos and digital terrain models, managers could be more empowered to spatially track the progress of loading activities. Outputs can also be used to perform volume calculations in order to determine the amount of material that has been mined, as well as the amount of material that remains on a block. This can in turn inform decision making regarding the short-term schedule.

6.5 General

It is recommended that Kumba Iron Ore applies RPAS technology at their operations in the Northern Cape to improve decision making related to block lifecycle activities. Although Kumba has already introduced RPAS technology for a variety of different applications, it has not specifically focussed on applying RPAS technology for monitoring block lifecycle activities.

It is recommended that additional research be performed to better understand how to optimally apply RPAS technology to collect data for fragmentation analysis. A suggestion would be to test a variety of cameras at different flying heights. Tests should be conducted across a variety of material types. One will need to ensure that a suitable RPAS unit is identified for this work. It is suggested that the flying height for future test work starts at 50m as it was seen that flying at heights above this does not yield the desired resolution.

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APPENDICES

Appendix 1 – Job Feasibility and Safety Assessment

Job Feasibility and Safety Assessment	UAV & Drone Solutions (PTY) Ltd.	Document Number:	Annexure 5
		Revision:	V1.6
		Revision Date:	12/12/2016
		Pages:	One (01)

JOB FEASIBILITY AND SAFETY ASSESSMENT				
Client:	Contact No:		Date:	
Task:	Location:		Check the following and address as needed (tick as applicable)	
Sketch # 1 of area (if necessary)	Sketch # 2 of area (if necessary)		1. Maps and charts available and checked	✓
			2. Weather, within limits for machine and operation	
			3. NOTAMs	
			4. Possibility of public moving into area	
			5. Footpath/right of way	
			6. Landing area including alternate	
			7. Ability to maintain 50M from public	
			8. Obstructions (buildings Trees)	
			9. Possible interference (Power lines/antennas)	
			10. Ability to maintain visual line of sight	
			11. Controllers ability matches location/task	
			12. Permission of any landowners	
			13. Privacy	
			14. Local restrictions, by laws	
Pilot:	Signature:	Crew:	Signature:	
Comments:				

Appendix 2 – Site Process Document

UDS Site Process Document	UAV & Drone Solutions (PTY) Ltd.	Document Number:	Annexure 10 a
		Revision:	V1.6
		Revision Date:	12/12/2016
		Pages:	Two (02)

Location Information				
Date				
Time of arrival				
Time of departure				
Scope of work				
Pilot-in Command				
Estimated # flights				
Area of operation				
GPS Coordinates	Longs		Lats	
Radio frequency				
RPA tail number				
		Tick	Safety	Yes or No
Landowner permission	PRINT			
Weather forecast	PRINT		Safe to operate	
Solar flare activity	PRINT		Safe to operate	
Yes or N				
Restricted airspace				
Danger Zones				
No fly zones(Client Specific)				

Pilot and observer information				
Name	Contact no	Next of kin	Contact no	Signature

1

EMERGENCY INFORMATION

Service	**Contact no**	**Confirm if operational**	
		Yes	**No**
Ambulance			
Hospital			
Fire station			
Police station			
Security service			
Land owner			
SACAA			
Nearest Aerodrome			
Other:			

Pilot in command – Acknowledgement that all actions have been taken and work can commence safely:

Name: ________________________ **Date:** ______________ **Signature:** ___________________

Safety manager – Acknowledgement that all actions have been taken and work can commence safely:

Name: ________________________ **Date:** ______________ **Signature:** ___________________

Appendix 3 – Pre-Flight Checklist

	OPERATIONS & PRE-FLIGHT	**UAV & Drone Solutio**		Document Nur	Annexure 12
				Revision:	A1.6
	CHECKLIST	**(PTY) Ltd.**		Revision Date:	2016/12/12
				Pages:	One (01)
	EXTERIOR PRE-FLIGHT CHECKS	**Flight No:**		**Flight No:**	
No	**DESCRIPTION**	**CHECK**	**COMMENTS**	**CHECK**	**COMMENTS**
1	Inspect Airframe/ Fuselage, wings, tail, etc. for damage	✓			
2	Inspect motor(s) & Propeller(s) & ensure all are secured corre	✓			
3	Ensure wings, mounts, arms are fitted to airframe correctly and securely & check all flying wires & struts	✓			
4	Ensure main landing gear and wheels are functioning correctly	✓			
5	Ensure all controls surfaces are secure & that movement is unimpeded and correct	✓			
6	Inspect any/ all steerable wheels, etc. must be secured and functioning correctly	✓			
7	Ensure all hatches & latches are secured	✓			
8	Ensure all aerials & antennae are secured to aircraft appropria	✓			
9	Complete the appropriate paperwork	✓			
	INTERIOR PRE-FLIGHT CHECKS	**Flight No:**		**Flight No:**	
No	**DESCRIPTION**	**CHECK**	**COMMENTS**	**CHECK**	**COMMENTS**
1	intended mission	✓			
2	correct location	✓			
3	Inspect Batteries and cables for damage or signs of wear due to vibration, ensure that all equipment is secured and correctly located	✓			
4	correct function. Ensure all are securely located & all leads are undamaged.	✓			
5	Ensure servo/ stepping motors are secure & that their function is correct & unimpeded	✓			
6	Check COG is correct when all batteries and payloads are installed	✓			
7	Ensure all required telemetry to & from aircraft is functioning correctly	✓			
8	Ensure aircraft operates correctly in all control modes	✓			
9	Check Gimbal operation	✓			
PILOT SIGNATURE :		**DATE:**			
OPERATOR :		**DATE:**			

Appendix 4 – Orthophoto at 40m

Appendix 5 – Orthophoto at 80m

Appendix 6 – Orthophoto at 120m