Mining Surveillance Application Using a CubeSat Constellation

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Sustainable Development Goals Contributed Towards:

- Good Health and Well-being
- Decent Work and Economic Growth
- Industry, Innovation and Infrastructure
- Responsible Consumption and Production
- Life on Land
- Partnerships for the Goals

1. Need

The mining industry is one of the largest in Africa with the Republic of South Africa (RSA) employing nearly half a million-people its mining sector alone [1]. Such a vast number of employees, together with the nature of the job, leaves a large amount of room for risk and management issues. The main risk involved is related to seismic activity and ground movements in the area – with sources reporting 77 total deaths in the industry in 2015 and 73 in 2016 [2]. Not all mines implement a system where these risks are mitigated and those that do provide minimal support and coverage for these high-risk areas. The current system that is used by mines involves the use of seismic sensors placed onsite to collect seismic data about the region. The data is then collected once a month via an aeroplane flyover. This system results in a low frequency of area coverage, a pilot at risk, and accidents that can take months to resolve. Drones have been considered to reduce the risk compared to a manned flight, however, they are limited to near-perfect weather conditions and would have to work in complex formations without improving revisit times. A more frequent coverage of these high-risk areas will enable early detections and warnings to be given long in advance to the respective parties involved. This, in turn, will save lives by providing a safer working environment as well as enable development in the surveillance of other mining related activities, such as optimisation of material extraction and environmental protection. It is well known that mining activities can introduce many environmental hazards and damage to the surrounding regions. By monitoring the effect and spread of these hazards - such as dangerous chemicals and soil erosion - one can work towards making mining more sustainable and less harmful to the surrounding environment.

2. Mission Objectives

The main mission objectives are highlighted and are given in descending order of priority below:

1. Monitor irregular seismic activity near mines.
2. Measure and detect deformations and movements in land surfaces at a shorter revisit time than current systems.
3. Identify active and inactive mines to analyse environmental effects.
4. Enlarge current mine-sensor coverage by relaying their data to their respective ground stations (GS).
5. Measure the mineral contents of mined heaps.

3. Concept of Operations

This section summarises the operation of the aforementioned mission.

- Space segment role:
    - Monitor seismic activity and ground deformations
    - HS analysis
    - On-board image processing
    - Data storage and relay thereof
- Launch segment and constellation design:
    - A summary of the sun-synchronous orbit (SSO) constellations with their respective local time of day and night (LTDN) is seen in Table 1

Table 1: Space Segment Summary

Constellation	# Satellites	Altitude	Inclination	Angular Separation	Swath	LTDN
HS	12	500 km	97.39°	5.8939°	9 km	10am/10pm
SAR	8	500 km	97.39°	13.4981°	50 km	12am/12pm

- Ground segment role:
  - Ground station:
    - Receive data
    - Satellite control
    - Data processing
    - Transfer important sensor information to relevant mining companies
  - Mine stations:
    - Receive and store ground-based sensor data

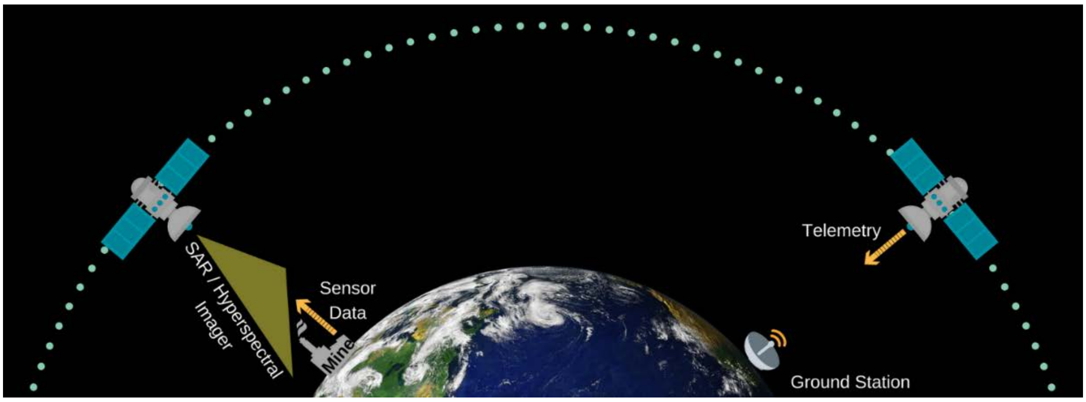

Figure 1: Concept of Operations

Figure 1 provides an overview of the entire system. There will be two types of 6U CubeSat satellites that are identical except for the observation payloads; one with a synthetic aperture radar (SAR) as payload and the other a hyperspectral (HS) imager. These satellites will be grouped into two constellations, one with 12 HS imager satellites and the other with eight SAR satellites. Each satellite will be able to store the payload data in addition to the ground sensor data from the mines and transfer all the telemetry to the GS.

4. Key Performance Parameters

Detecting seismic activity around mines is currently being implemented, however the data is only being retrieved around once a month. To effectively detect irregular seismic activity and prevent disasters by evacuating an area early will require a revisit time of at least once per day to collect the data. The data will be collected by seismic sensors placed around 400 m deep in and around the mines, which will be transmitted to the satellites. The sensors can measure ground velocity and acceleration or a combination of the two. The proposed constellation will allow for a communication-revisit time of at least four times per day per constellation.

Monitoring surface movements and deriving elevation models of mines will be done using a SAR. The SAR will need to be small and light to fit into the satellite. A spatial resolution of 25 m is achieved by using new integrated SAR (InSAR) technologies [3].

A HS imager will allow the monitoring of mine emissions and the mineral content of the mined heaps. The imager has a range of up to the near-infrared band (wavelengths of around 1000 nm) which is useful in monitoring the vegetation index surrounding the mines [4]. The HS imager, equipped with a telescope, can have a ground sampling distance (GSD) of at least 5 m at a 500 km altitude. The required telescope is a Cassegrain-type and requires an effective focal length of 0.55 m and lens diameter of 9 cm. The actual length of the telescope tube will be roughly 0.25 m.

5. Space Segment Description

5.1 Component Overview

An overview of components that will be used for the mission is listed and briefly commented on in Table 2. CAD diagrams are given in Figure 2 and Figure 3 and the component numbers given in Table 2 corresponds to the respective component numbers in the figures.

Table 2: Overview of Components with Mass and Volume Budget

No.	Component	Comment	Mass (g)	Dimensions (mm)
Common				
1	ADCS	CubeADCS	617	90 x 96 x 75
2	Propulsion	Busek BmP-220 Plasma Thruster	580	95 x 95 x 40
3	OBDH	CPU, Mass Storage, S-Band Transceiver and Flight Module	300	95 x 95 x 45
5	Solar Panels	Mass given for 18 Panels	900	100 x 100 x 3
HS Satellite Only				
4	Power Supply	EPS and Battery	195	95 x 95 x 95
6	Antennas	Helical Antennas	800	Ø 40 x 61.18
7	HS Imager	SCS Gecko HS Imager	480	97 x 96 x 60
8	Lens	For increased GSD @ 500km	1000	Ø 95 x 240
Totals Hyper Spectral			**4872**	**200 x 100 x 300**
SAR Satellite Only				
4	Power Supply	EPS and Battery	4875	95 x 95 x 95
9	Boom Deployment System	[5]	1055	95 x 95 x 50
10	Antenna Booms	4 Booms Deploying [5]	109	Ø5 x 1600 & Ø5 x 800
11	High Gain Membrane Antenna	Copper-coated polymer membranes [5]	336	1600 x 3200 x 2
12	InSAR	SRI-CIRES Payload [3]	1500	95 x 95 x 140
Totals SAR			**10272**	**200 x 100 x 300**

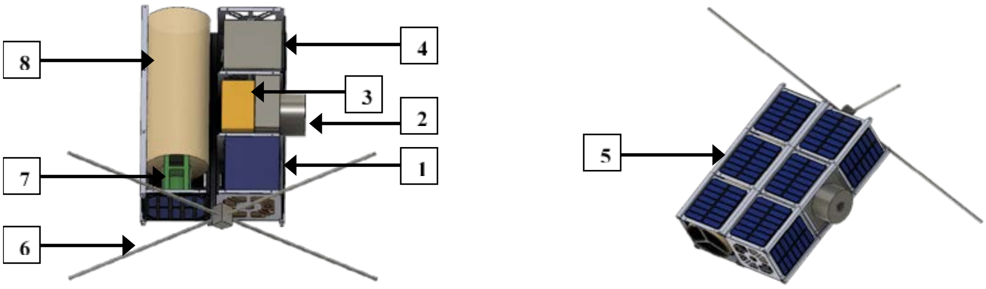

Figure 2: Hyperspectral Imager Payload Satellite External (Left) and Internal (Right)

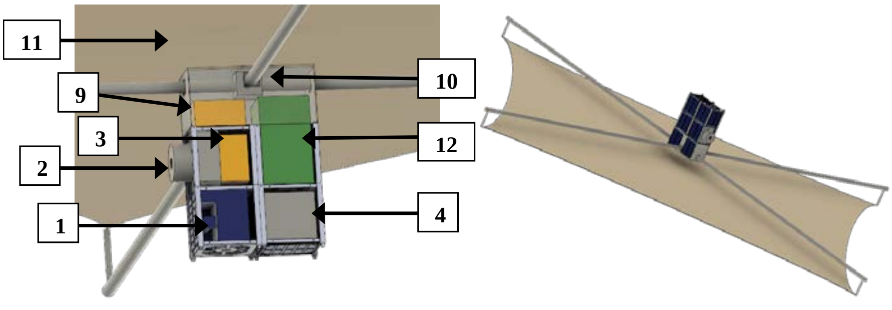

Figure 3: SAR Payload Satellite External (Right) and Internal (Left)

5.2 Link Budget

The HS payload satellite will use a helical antenna whereas the GS and the SAR payload satellite will use a parabolic dish antenna and a patch-antenna array, respectively. The SAR uses an S-Band frequency of 2.9 GHz for the synthetic imaging. Thereafter, the on-board Comms module will then use the patch-antenna array to downlink the payload data to the GS.

The modulation scheme for data transfer will be QPSK and the respective S-band frequency is 2.45 GHz. The downlink data transfer rate is roughly 65 Mbps [6]. With regards to the HS satellite, this transfer rate will allow for 100 images containing 20 spectral bands to be downlinked to a GS in around 540 seconds which is less than the average access time of each satellite. All tracking and command information together with the relay of ground-sensor data will be transferred at 435 MHz to save power and be robust.

The maximum transmit power on both types of satellites is equal to 7.76 dBW with an expected carrier-to-noise ratio of 58.6 dB when transmitting to the GS. The 16 m diameter GS antenna has a gain of 50.05 dB. The five turn helical antenna on the HS satellites results in a gain of 11.4 dB, where the SAR satellites' antenna gains are 33.24 dB.

5.3 Power Budget

The InSAR requires 192 W to operate for nine minutes [3]. As such, the required capacity was calculated as 64 W-hr. The nominal bus voltage is chosen as 15 V which implies a battery configuration of two parallel strings of 5 Li-Ion cells rated at 2 Ah each. Therefore, full capacity is equal to 390 W-hr when at the maximum bus voltage of 19.5V, resulting in a battery-mass of 4.875 kg for the SAR satellites.

The largest arclength that the satellites would travel across RSA is around 14°. This implies that at worst case the SAR must operate around four to five minutes. Consequently, this ensures that the satellite has adequate power for other subsystems and allows for monitoring of the neighbouring countries as well.

The ADCS, OBDH and Comms on both satellites will use less than 8 W at maximum operating power. During operation, the HS imager consumes 3.5 W, thus the mass of the batteries is smaller than those on the SAR satellites. Furthermore, the required battery capacity was calculated as 15.6 W-hr when considering a maximum total operating power of 11.35 W with an orbital eclipse time of 33.85 minutes.

5.4 Delta-V Budget

The delta-V budget was calculated for manoeuvring the satellites into their respective constellations as well as orbit maintenance throughout the mission lifetime. The delta-V required to enter the smaller transfer orbit for the HS satellites was calculated as $\Delta V = 1.03974$ m/s per satellite and will be the same to exit this orbit. The delta-V required for orbit maintenance was calculated as $\Delta V = 69.03$ m/s per satellite over a lifetime of 5 years. These values were calculated using 80g of fuel to start with which leaves around 16.46g of fuel at the end of the mission for deorbiting purposes [7].

Using the same procedure as for the HS satellites, the delta-V required to enter and exit the small transfer orbit for the SAR satellites is $\Delta V = 1.464$ m/s per satellite each time. The lifetime requirement for orbit maintenance was calculated as $\Delta V = 32.74$ m/s per satellite. Also starting with 80g of fuel, the total fuel used will be equal to 69.43g leaving roughly 10.57g of fuel for deorbiting purposes.

6. Orbit and Constellation Description

For Earth observation, SSOs were chosen for image continuity at an altitude of 500 km and an inclination of 97.4°. The HS payload requires a well illuminated Earth surface, as such, a local 10pm/10am orbit is chosen. Consequently, the eclipse time for this SSO is 33.85 minutes. The SAR payload does not require illumination. Therefore, a 12pm/12am orbit is chosen to reduce the battery sizes as the SAR payload is relatively large. Static surveillance is not possible at the chosen altitude. As such, the difference in argument of perigee for the HS and SAR constellation was calculated as 5.8939° and 13.4981°, respectively with each having a swatch overlap of 1%.

The HS imager requires a GSD of less than 5 m. Therefore, only a 2.5° off-nadir pointing angle can be achieved before the GSD is greater than 5 m. This results in an effective swath of 22 km wherein a 9 km image can be captured. The SAR has a swath of 50 km, therefore fewer satellites are required. The swath and orbital tracks for the SAR constellation can be seen in for a six-day cycle, indicating coverage of RSA. Similar results were found the HS constellation.

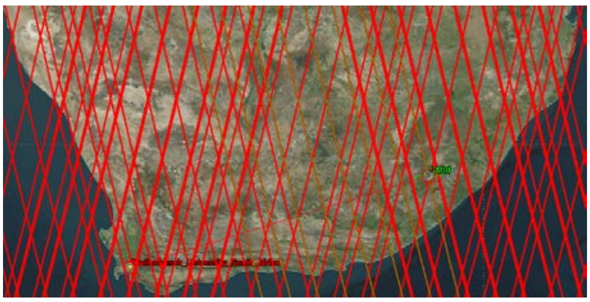

Figure 4: Six Day Coverage Tracks for SAR Constellation

Full coverage of RSA can be achieved by using 12 HS and eight SAR satellites, as determined by using the Systems Tool Kit (STK) software package developed by AGI technologies. The simulation was run between Julian Dates 2458242.92 and 2458248.92. This resulted in a mean payload revisit time of five and two days for the HS and SAR payload, respectively. The communication revisit time for each satellite is 4.5 times per day. These results are summarised in Table 3 and Table 4.

Table 3: Constellation Means for a 6 Day Period (Relative to a Static Point in RSA) for Comms

Constellation	# Satellites	Elevation	Range	Access Time	Total Access Time	Accesses
HS	12	10.1°	1901 km	556 s	182331 s	328
SAR	8	10.2°	1912 km	554 s	122514 s	221

Table 4: Constellation Means for a 15 Day Period (Relative to a Static Point in RSA) For Payload Purposes

Constellation	# Satellites	Elevation	Range	Access Time	Total Access Time	Accesses
HS	12	87.8°	506.9 km	6.2 s	18.7 s	3
SAR	8	88.3°	506.8 km	1.24 s	11.1 s	9

7. Implementation Plan

The project will be handled primarily by SU along with various mining companies in RSA (e.g. Stone3 and Exxaro). The GS centre will be the existing one at SU in their Electronic Systems Laboratory (ESL). CubeSpace will be used for CubeSat parts such as the ADCS and the shell of the satellite. The Gecko HS imager will come from Space Commercial Services Aerospace Group (SCS) and the SAR is currently being developed and tested by SRI International and funded by NASA [3].

Current infrastructure exists somewhat in the form of ground seismic sensors, but not all mines have them in place and therefore most will have to install them. The satellite will send this sensor data along with the images taken to the existing ESL GS with every pass over. The satellites will be launched as a piggyback to another project at a 500 km orbit, thereafter they will perform orbital manoeuvres to get into their respective constellations.

A risk matrix of size 5x5 was used to rank the risks on probability vs severity ranging from a scale of one to five, with the score being the product of the two. High risk scores are in red, medium risk scores are in yellow and low risk scores are in green. The potential risks involved are shown in the Table 5 below.

Table 5: Project Risk Analysis

	Risk	Impact	Probability	Risk Score	Effect
1	Communications failure	5	3	15	Complete Mission failure
2	Inaccurate ADCS	5	2	10	Main mission failure, only relay possible
3	Thruster failure	3	2	6	Loss of satellite in constellation
4	Debris impact	3	2	6	Can range from subsystem damage to loss of satellite
5	Delay in developing SAR technologies	2	3	6	Delay in project
6	Funding issues	2	3	6	Delay in project
7	Launch vehicle failure	4	1	4	Delay in project, loss of money

8. References

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