D2.2

White Paper: Guidance and Considerations for Deployment of Hyperspectral Imaging UAVs at Mining Operations

Project

Acronym:	**m4mining**
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Consortium:	**NORCE Norwegian Research Centre AS (NORCE),** Norway **Norsk Elektro Optikk AS (NEO)**, Norway **Helmholtz Zentrum Potsdam Deutsches GeoForschungsZentrum (GFZ)**, Germany **Luleå Tekniska Universitet (LTU)**, Sweden **Prediktera AB (PDK)**, Sweden **Geological Survey Department (GSD) of Ministry of Agriculture, Rural Development and Environment of Cyprus (MOA)**, Republic of Cyprus (MOA-GSD) **Panepistímio Patrón (UoP)**, Greece **University of Queensland (UQ),** Australia **ReSe Applications LLC (ReSe)**, Switzerland

Deliverable

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Title:	**White Paper: Hyperspectral Imaging UAV Guidance and Considerations for Deployment at Mining Operations**
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Reviewers:	**Friederike Koerting**

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1. Executive Summary

The purpose of Deliverable D2.2 is to provide content for a White Paper, that will be distributed publicly, to help inform the resources sector about compliance and safety considerations for deploying hyperspectral imaging (HSI) cameras integrated with uncrewed aerial vehicles (UAVs). The deliverable will be showcased with a Minerals Industry Advisory Board then, following feedback from the board, it will be updated and published to the broader resource sector community by the Sustainable Minerals Institute.

D2.2 supports the objectives of M4Mining by outlining the safety, logistical and compliance aspects of existing technology, understanding the regulatory landscape the technology must operate within, and pointing to the directions that future technology should take to overcome some of its challenges. In particular, D2.2 addresses objective II, in providing insights that contribute to developing *"a reliable multi-sensor UAV hardware and software infrastructure for deployment"*, as well as objective III; *"Establish best practice in deployment"*.

The White Paper first introduces aspects around UAV-HSI equipment specifications and management, including data curation, and then outlines aviation regulations and compliance most relevant to UAV-HSI. The paper highlights logistical considerations for deploying a system in mine environments which are most important for planning and risk management. Finally, the paper concludes with an outline of future directions driven by both regulatory developments and resource sector needs.

2. Introduction

The m4mining Workpackage 2 seeks to establish the functional, performance and safety requirements for hyperspectral cameras integrated into uncrewed aerial vehicle platforms (UAV-HSI). To this end, Deliverable D2.2 is a White Paper that analyses the logistical aspects of deploying UAV-HSI and the compliance requirements set by international and national aviation authorities and standard-setting organisations.

The White Paper (Appendix 1) will be distributed to the resources sector, to help the sector engage with the technology by better understanding key aspects of planning and regulatory obligations.

3. Contribution to the top-level objectives

Deliverable D2.2 directly addresses Objective III - Establish best practice in deployment.

Deliverable D2.2 provides insights that contribute to a better understanding for achieving Objective II – Develop a reliable multi-sensor UAV hardware and software infrastructure for deployment.

4. Work Carried out

The work elements that contributed to the White Paper include:

- Early deployment of a Hyspex Mjolnir UAV-HSI system, to a legacy mine site in Australia. This work involved field support from the Queensland Department of Resources (Geological Survey of Queensland). This case study provided a number of insights around the logistics of transporting equipment across international borders, insurance, LiPo battery management and operating UAV-HSI in remote locations. The work was carried out by UQ and NEO.

- Review of aviation authorities protocols, regulations and compliance procedures – distilling down into essential messages and links to source material. This work was carried out by UQ, with contributions from NEO.

- Formation of a Minerals Industry Advisory Board and subsequent discussion with the Board Members about operating in mine and exploration environments. This work was carried out by UQ.

As discussed in August 2023 and indicated to the M4mining Project Officer, the deliverable D2.2 associated with Task 2.2 was intentionally pushed back to ensure the quality of stakeholder and MIAB input in the White Paper. The D2.2 could have been provided according to deadline but it was felt that the gold standard is to ensure that the White Paper involves as much industry participation as possible, within the confines of the project, in order to position for the highest impact.

The MIAB gave verbal guidance on the complexities of operating in active mine sites (especially the MIAB member Plotlogic). The MIAB also provided crucial logistical support in the planning and deployment of a drone survey over the legacy Mary Kathleen Mine. This included collaborating with us to define the safety protocols and logistics for the field deployment, which provided valuable insights for the White Paper (especially the MIAB member Geological Survey of Queensland). Finally, Rio Tinto provided information on their requirements for drone service providers to operate under the Basic Aviation Risk Standards program (BARS).

5. Main Results Achieved

The output of Deliverable D2.2 is the production of a White Paper. The deliverable is linked to milestones 2.2 and 2.3.

The White Paper shows that current, commercial UAV-HSI systems are relatively complex, and subject to aviation standards and regulations that must be met. The amount of ancillary equipment and field support required to deploy UAV-HSI is not straightforward. The White Paper provides guidance so that the resources sector can more easily engage with the technology. In particular, the White Paper identifies 4 areas of future development related to:

1. Regulatory development.
2. Onboard data processing and real-time capabilities. Data security, cloud storage & automated backup.
3. Remote operations centres (ROCs).

6. Progress Beyond the State of the Art

The White Paper of D2.2 identifies how the core objective of M4Mining goes beyond the state-of-the-art, in developing a system to deliver near real-time HSI data and interpretations. The White Paper also outlines 3 areas of future development that could represent second iterations of M4Mining, to help upscale the innovation and adapt it so that it is more market-ready (see above).

7. Impact

The White Paper of D2.2 directly addresses the ambition of M4mining to make an impact by helping the technology become available to and more easily usable by customer groups, who would otherwise require dedicated researchers. The Deliverable D2.2 lays the groundwork to guide how future technology development could be more user-friendly.

8. Links

Deliverable D2.2 helps contribute to WP6 (case studies where UAV-HSI systems are deployed in mine environments), WP9 (industry impact) and WP10 (dissemination and exploitation of results).

9. Communication, Dissemination and Exploitation of Results

The White Paper of Deliverable D2.2 will be released as a non-scientific report for the resources sector. The White Paper will be first circulated amongst the M4mining Minerals Industry Advisory Board for final comment. There will be a final step of peer review by an industry subject matter expert. Then we expect to widely disseminate the White Paper to the industry networks available to the Sustainable Minerals Institute (UQ) and via social media, as well as potentially publishing it on UQ websites.

An important objective in the dissemination of the White Paper will be to canvas the industry for appetite for support of the M4mining initiative, to take developments forward (as identified in the White Paper).

10. Peer Reviewed Articles

N/A

Appendix 1: White Paper: Guidance and Considerations for Deployment of Hyperspectral Imaging UAVs at Mining Operations

D2.2 - APPENDIX 1

White Paper: Guidance and Considerations for Deployment of Hyperspectral Imaging UAVs at Mining Operations

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Glossary

Abbreviation	Explanation
AAUS	Australian Association for Uncrewed Systems
AGL	Above ground level
AROC	Aeronautical Radio Operator Certificate
BVLOS	Beyond visual line of sight, synonymous with beyond line of sight, BLOS
BARS	Basic Aviation Risk Standard program
CASA	Civil Aviation Safety Authority, relevant for Australian regulations
EASA	European Union Aviation Safety Agency
GPS	Global Positioning System
GNSS	Global Navigation Satellite System
HSI	Hyperspectral Imaging
ICAO	International Civil Aviation Organization
LUC	Light UAS operator Certificate,
MTBF	Mean Time Between Failures
MTOM	Maximum Take-Off Mass, synonymous with Maximum Take-Off Weight (MTOW)
NAA	National Aviation Authority
ReOC	Remotely Piloted Aircraft Operators Certificate
RePL	Remote Pilot Licence (CASA)
RID	Remote Identification, either built-in by manufacturers or separate modules that can be attached to UAVs for tracking and identification. These are required in the USA and Europe.
STS	European Standard Scenario, for UAV operations
SWIR	Shortwave infrared
VNIR	Visible to near infrared
UAV	Uncrewed Aerial Vehicle, synonymous with Drone, Remotely Piloted Air System (RPAS), Remotely Piloted Aircraft (RPA), Uncrewed Aircraft (UA), or Uncrewed Aerial System (UAS)
UAV-HSI	Uncrewed Aerial Vehicle integrated with an imaging spectrometer capable of hyperspectral imaging the visible near-infrared +/- short wave infrared
VTOL	Vertial Take-Off and Landing UAV, synonymous with Powered Lift
VLOS	Visual Line of Sight

1. Introduction

Imaging spectrometers measure and map the composition of rocks, plants and soils, resolving a wide range of spectral bands in the infrared wavelength range of the electromagnetic spectrum (otherwise known as hyperspectral imaging). The technology promises to be particularly useful in the resources sector when combined with uncrewed aerial vehicles, due to the flexibility these platforms offer for repeat, accurate, high-resolution remote sensing over mine areas that are inaccessible, remote or unsafe.

The technology is interoperable. With many varied applications, hyperspectral imaging has been used extensively in astronomy, planetary science, agriculture, food processing, zoology, and geosciences. In the resources sector its potential applications include mineral vector mapping (exploration), characterisation of fault-fracture composition and distribution (geotech), open pit and blast bench mineral mapping and texture mapping (geometallurgy and ore-waste tracking), stockpile mineralogy and particle size characterisation (reconciliation), plant species phenotyping and health monitoring (environmental management), moisture detection and iron-oxide characterisation (tailings management), amongst other things.

This White Paper provides guidance and operational considerations for uncrewed aerial vehicles (UAVs) with a hyperspectral imaging camera (HSI) payload. We refer here to the combined system as UAV-HSI. The size and weight of hyperspectral imaging cameras are such that the UAVs that carry them tend to be ~25 kg in weight or higher. The guidance presented is specific to that UAV weight, as well as safety and logistical considerations associated with the operation of the UAV-HSI in the field. This document is not intended to be an operations manual but instead to provide a starting point for companies and service providers planning to deploy UAV-HSI.

We first introduce aspects around UAV-HSI systems including data curation, then outline aviation regulations and compliance most relevant to UAV-HSI. We highlight logistical considerations for deploying a system in mine environments which are most important for planning and risk management. Finally, we conclude and outline future directions.

For a broad review of the application of imaging spectroscopy to the resources sector we refer readers to Koerting et al., 2024. For a summary of the role that UAV-HSI could play in the monitoring of tailings and mine waste, we refer readers to the M4Mining Milestone 9.1 document (Micklethwaite et al., 2024).

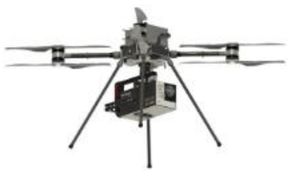
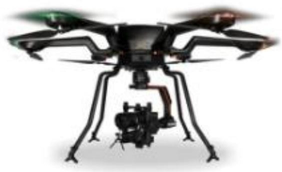
2. UAV and Hyperspectral Sensor Specifications

2.1 System Components and Typical Dimensions

Commercially available UAV-HSI systems are rapidly evolving and are likely to simplify over time. Nonetheless, present models have are a large number of components that operators should be aware of for logistical and risk assessment considerations.

As outlined in Table 1, UAV-HSI systems are large instruments. It is not unusual for field deployments to require a minimum of 3-5 large pelican cases, containing the airframe, HSI camera (with or without integrated LiDAR), gimbal, landing gear, adapters, radio antennae, cables, position lights, rotor blades, spare parts, and batteries (minimum 3 sets). The blades are typically unguarded and when rotating they are capable of inflicting serious injury. Further considerations include the airworthiness of airframes, components, and batteries, and these must be documented and tracked. For example, the recommended lifespan of batteries is up to 150-300 charge cycles under optimal conditions, and modern UAVs use brushless motors, which have extended lifespans (up to 10,000 hours). Nevertheless, motors are known to unexpectedly fail, battery health needs close monitoring, landing gear becomes damaged with hard landings and rotor blades require regular checking. Monitoring and recording the use of these components relative to manufacturer recommendations is important for safe operations.

Table 1 - Examples of typical UAV dimensions and basic performance criteria (wind, temperature) used to carry HSI cameras.

Name	Region	Source
Model	Hercules X8 (BS)	NOA Acecore
Image		
Dimensions	1091 mm (diameter motor to motor)	1680 x 1680 x 840 mm (LxWxH)
MTOM	25 kg	37 kg
Maximum flight time (controlled conditions)	55 min	60 min
Realistic flight time with HSI camera	12 min	20-30 min
Wind resistance	35 knots, 18 ms^{-1}	~30 knots, 14 ms^{-1}
Operating temperature	-20°C to +40°C	-15°C to 50°C

In addition to the hardware components and considerations outlined above, firmware and software is an important component of UAV-HSI systems. The nature of HSI imaging requires precise measurement of altitude, pitch, yaw and role and location. UAV-HSI systems use an high quality Inertial Navigation Systems (INS), an Inertial Measurement Unit (IMU), and a differential Global Navigation Satellite System (GNSS) to achieve this. In addition, flight speeds and camera alignment require careful control, which is dependent on flight planning software. There are a number of planning software on the market (e.g. Pix4D for photogrammetric and multispectral surveys, DroneDeploy, UgCS for multiple UAV models and sensors, Mission Planner, PrecisionFlight etc). In our experience, UgCS provides the most versatility in flight planning for UAV-HSI, although it is not the most intuitive software.

The firmware and software component of UAV-HSI are mission critical. This is particularly true for remote mine locations, where there may be no reliable access to internet or mobile networks. As a result, **it is important that operators regularly update firmware and software prior to missions**.

2.2 Stability, Gimbal, etc.

The use of gimbals is necessary for multirotor pushbroom UAV to stabilise the imaging payload and to maintain a consistent line-of-sight. The inherently unstable multirotor UAV, due to rotor movements and environmental factors like wind, requires the use of gimbals to counteract the constant motion and keep the imaging payload steady. The gimbal takes power from the 52V of the UAV batteries, while also providing 22V for the camera sensor itself. It works also as a passthrough of the radio signal for remote access of the camera sensor.

2.3 Hyperspectral Sensors

Depending on the goal and application of a UAV-HSI survey, various spectral wavelength ranges are appropriate. The more common HSI wavelength range has been visible-near infrared (VNIR), with applications to plant phenotyping, plant health, water quality and the mapping of iron oxide minerals suitable for understanding acid rock drainage (c.f. Micklethwaite et al., 2024). However, recent years have seen the emergence of short-wave infrared (SWIR) instruments and co-aligned VNIR-SWIR, more suitable for a broader range of material characterisation, including mineral mapping (Koerting et al., 2024). Table 2 features a range of HSI cameras suitable for UAV platforms.

HSI cameras can be thought of as having two different types of resolution; spectral and spatial resolution. The spectral resolution is the dimension of the infrared wavelength that can be measured in nm, with the narrower a band the better because more features can be resolved in the spectrum. Spectral resolution is continually improving and HSI cameras for UAVs now have spectral resolutions equivalent to or better than satellite systems. The spatial resolution is ground sampling distance (e.g. pixel size) and is dependent on the sensor and the altitude at which the data is collected. Typical spatial resolution ranges are a few centimeters for UAV-HSI (as compared to tens of metres from satellite platforms).

Note that bit depth of the HSI camera is an additional parameter to consider. Bit depth indicates the precision of the intensity values recorded for each voxel (ie. 3D pixel). Common bit depths are 12-bit, 14-bit, or 16-bit, indicating the range of possible intensity values. It is a combination of spectral resolution, spatial resolution and bit depth that contributes to the size of a hyperspectral data cube. The size of the collected imaging data has logistical implications for data management, storage, and processing.

Table 2 - Various brands, sensor manufacturers, and names of hyperspectral instruments with corresponding specifications of spectral wavelength ranges.

Name (Service provider/ brand/ name of instrument)	Wavelength range	Type of data acquisition	Spectral bands and sampling
NEO/HySpex Mjolnir VS-620	VNIR (400 – 1000 nm) SWIR (970 – 2500 nm)	Pushbroom	200 bands @ 3nm; 300 bands @ 5.1 nm
Headwall Nano HP	VNIR (400 – 1000 nm)	Pushbroom	340 bands @ 1.76 nm
Headwall Micro 640	SWIR (900 – 2500 nm)	Pushbroom	267 bands @ 6 nm
Headwall Co-Aligned HP	VNIR (400 – 1000 nm) SWIR (900 – 2500 nm	Pushbroom	340 bands @ 1.76nm; 267 bands @ 6 nm
Senop Rikola	VNIR (500 – 900 nm)	Frame-based snapshot	50 bands @ 8 nm
Senop HSC-2	VNIR (500 – 900 nm)	Frame-based snapshot	up to 1000 freely selectable bands @ 6 – 18 nm,
Specim AFX10	VNIR (400 – 1000 nm)	Pushbroom	224 bands @ 2.68 nm
Specim AFX17	VIS-NIR (400 – 1700 nm)	Pushbroom	224 bands @ 3.5 nm
Cubert GmbH ULTRIS X20	UV-VNIR (350 – 1000 nm)	Snapshot	164 bands @ 4 nm
Telops Hyper-Cam Nano (announced April 2024)	VIS – NIR (400 – 1700 nm)	N/A	N/A
Haip Solutions – Black Bird 2	VNIR (500 – 1000 nm)	Hovering Linescanner	100 bands @ 5 nm
Resonon Pika L	VNIR (400 – 1000 nm)	Pushbroom	281 bands @ 2.7 nm
Resonon Pika IR-L	NIR (925 – 1700 nm	Pushbroom	236 bands @ 5.9 nm
BaySpec OCI-UAV	VNIR (600 – 1000 nm)	Pushbroom and Snapshot	100 nds @ 5 nm

2.2.1 General considerations

As with the UAV platform, HSI cameras have a durability and reliability. Mine environments are harsh and components wear over time. The following environmental factors influence whether a HSI camera is fit for purpose:

- *Temperature Range*: Mining sites can subject equipment to extreme temperature variations. The system should be able to operate reliably across these temperature ranges without performance degradation.
- *Humidity and Dust*: High humidity and dust levels can affect sensor performance. Systems with robust environmental sealing and protective measures are imperative.
- *Vibration and Shock*: The system should be rugged and able to withstand vibrations during flight but also during transport over rough ground.

Systems that involve easily sourced spare parts and require fewer cables and antennae are advantageous from an operational perspective. In addition, the battery life and availability of replacement batteries should be considered in the selection and deployment of UAV-HSI. A useful measure here is Mean Time Between Failures (MTBF), where those systems with high MTBF ratings indicate better reliability and lower rates of failure.

2.2.2 Calibration

HSI cameras, and co-aligned hyperspectral VNIR-SWIR systems in particular, may require regular calibration to ensure accurate and reliable data collection. The frequency and methods of calibration can vary based on the specific application, environmental conditions, and the manufacturer's standards. The frequency and ease of calibration of a system as well as the manufacturers service standards and locations in which calibrations can be performed should be considered. This is especially important in the mining context where systems need to perform robustly in remote locations to provide data for continuous operation. Frequent servicing schedules affect the usability of the system.

Considerations are:

- *Calibration Frequency*: Systems requiring less frequent calibration can be more advantageous in remote locations.
- *Field Calibration Capabilities*: A system that can be easily calibrated on-site using portable tools to reduces downtime and logistical challenges are advantageous.
- *Automated vs. Manual Calibration*: Automated calibration systems can simplify the process and reduce human error.

Reasons for Calibration are:

- *Sensor Drift*: Over time, sensors can drift due to environmental factors, aging of components, and general wear and tear. Calibration corrects for this drift to maintain data accuracy.
- *Spectral Accuracy*: Ensuring that the system accurately measures and records the correct wavelengths is crucial for applications such as material identification, vegetation analysis, and mineral exploration.
- *Radiometric Calibration*: This ensures that the system's response to light intensity remains consistent and accurate.
- *Boresight*: This is the misalignment angles between IMU (designed for tracking sensor rotations and acceleration) and camera frames of reference. The boresight parameters are determined by flying over highly accurate ground control points (GCPs) and conducting aerial triangulation on the resulting imagery. Cross-flight pattern-based boresighting is an alternative and well-established standard (Schläpfer, D.; Trim, S. 2024). For some systems, the boresight calibration must be completed before each survey, for others, such as the HySpex Mjolnir System, the boresight angles and correction matrices are provided with the camera and remain stable over a period of time (annual boresight calibration is recommended).

Regular calibration serves as a check on the instrument's overall health, identifying any potential issues before they impact data quality. Robust QA/QC routines of collected data can support this and indicate the necessity of a health check. While the frequency of calibration may vary a general approach can be followed:

1. Initial Calibration: When the system is first developed or before it is deployed for a new project, an initial calibration is performed to ensure it meets the required specifications and standards.
2. Routine Calibration:
    a. Regular Intervals: Many systems require routine calibration at regular intervals, depending on the application's precision requirements and the environmental conditions.

   b. Usage-Based Calibration: Calibration frequency may also depend on the amount of use. Systems used frequently in harsh conditions might need more frequent calibration.
3. Post-Event Calibration: After significant environmental events (e.g., extreme temperature changes, vibration during transport), systems may need to be recalibrated to account for any potential shifts in sensor performance.

Field Calibration: For some systems, calibration might be performed on-site prior to every survey.

2.2.3 Support and Service Agreements

Reliable technical support is crucial, especially when operating in remote locations. The availability and responsiveness of the manufacturer's support team can be a bottleneck for operations. Similarly, the ease of accessing maintenance and repair services are of importance as well. Manufacturers with global support networks or local partners can offer better service. Comprehensive warranty and service agreements should cover calibration, maintenance, and repairs, while purchase agreements that include aspects of training and support are an important consideration. UAV-HSI systems are relatively high-cost items of equipment but the long-term value of any maintenance and calibration offered should be considered as an offset to the initial costs, when comparing between UAV-HSI systems.

2.2.4 Other considerations - data management

Hyperspectral imaging generates a large amount of data. The UAV-HSI systems are no exception and they may generate more than 1 TB of data per hour. Data is generated by the HSI camera but also INS, IMU, GNSS/GPS, and any integrated digital cameras and LiDAR.

Data is both stored onboard the UAV and partially relayed to a base station set up (ground operator laptops etc). It is essential, that data stored onboard the UAV is transferred to backup devices after each flight, to avoid loss of data if there is a catastrophic failure of the UAV on the next flight. In the future, it may be possible to develop automated, fast data transfer protocols.

At present, these large data volumes and the necessary expertise that goes with processing, then interpreting the data, is a logistical challenge to the resources sector. Many industry professionals are time-poor and do not have the compute or expertise. Outsourcing the processing and interpretation of the data, is the easiest approach to overcome these challenges and this step in the process must be factored into project budget.

3. Compliance, Standards, and Safety

In this section, we point to aspects of compliance and aviation standards that are relevant to UAV-HSI systems operating in the resources sector (e.g. multi-rotor UAVs ~25 kg MTOM, or 25-150 kg MTOM).

Although UAVs have been used in some form for nearly a century, they only became mainstream in the last 15 years, driven by the advent of light-weight, compact digital cameras and improvements to battery and electric motor technology. This recent rise in popularity means that aviation standards and regulations are challenged and remain in flux. As a result, ***we recommend operators within the resources sector monitor national aviation regulators to ensure they remain compliant***.

Operators should also monitor the International Civil Aviation Organization (ICAO) guidelines and industry advocacy groups (c.f. Australian Association for Uncrewed Systems; AAUS) in order understand the direction regulations are changing into the future.

Most regulations make a distinction between commercial vs recreational UAV operations. Clearly, operations in and for the resources sector fall under commercial regulations. There are two types of commercial UAV operators relevant to the sector:

1. Contract service providers,
2. Direct uptake and integration into mine site operations (owner-operators).

In nations like Australia, this is an important distinction. Mining companies wishing to act as owner-operators need to ensure staff are trained and qualified on the equipment, maintain equipment and flight logs, and ensure they have appropriate accreditation etc. However, owner-operators have the advantage of being able to fly UAVs on their own land under the excluded category even for relatively heavy platforms (25-150 kg)[1], without the need to meet the same compliance requirements as a contract service provider.

The following sections introduce European Union (EU) and Australian regulations by way of example. Within the EU, these regulations are developed under the European Union Aviation Safety Agency (EASA); and in Australia, under the Civil Aviation Safety Authority (CASA). The main difference between both regulations is that EASA uses a risk-based approach that considers several parameters in regulating an operation, whereas the CASA uses the weight of UAV as the dominant factor.

3.1 Basic Considerations for UAV Compliance

Regulations in each country vary but there are some common parameters used to assess basic operations, guided by ICAO (Table 3):

- A form of registration (either pilots, or equipment or both).
- The height of flight operations above ground level.
- The type of UAV (single rotor, multi-rotor, fixed wing, vertical take off and landing)
- The total mass of the UAV and payload (MTOM), with an important regulatory threshold typically set at 25 kg MTOM.
- Whether the UAV is consumer grade/off-the-shelf, or privately built.
- The distance from persons.
- The restricted airspace regulations, for example, limiting UAV flights around airports, national parks and populated areas.
- The remote pilot's line of sight (VLOS or BVLOS).

[1] https://www.casa.gov.au/drones/get-your-operator-credentials/drone-weight-categories-and-requirements#Medium,excludedcategoryRPA

For our purposes, the UAV-HSI platforms on the market use consumer-grade, multi-rotor platforms. Their MTOM is typically <25 kg ranging up to ~40 kg (as outlined in Section 2, UAV and Hyperspectral Sensor Specifications). This point is revisited below.

A further factor is a shift within the sector to an increasing level of accreditation. Some resource companies require contract service providers to have achieved additional certification and accreditation beyond that required by Aviation Authorities. The BARS Program[2] from the Flight Safety Foundation provides audits and a "global" standard for aviation safety and risk management. This program was developed in collaboration with major resource companies. The International Standards Organisation has also established criteria for safe and optimal UAV operations (ISO 21384-3)[3].

Table 3 - Selection of useful sites summarising aviation authorities for UAV operations.

Aviation Authority	Region	Source
Civil Aviation Safety Authority	Australia	https://www.casa.gov.au/drones
Direccion General de Aeronautica Civi	Chile	https://www.dgac.gob.cl/operacion-de-drones/
European Union Aviation Safety Authority	Europe	https://www.easa.europa.eu/en/the-agency/faqs/drones-uas#category-regulations-on-uas-drone-explained
Transport Canada Civil Aviation	Canada	https://tc.canada.ca/en/aviation/drone-safety
International Civil Aviation Organization	United Nations	https://www.icao.int/safety/UA/UASToolkit/Pages/default.aspx

[2] https://flightsafety.org/bars-program-introduces-drone-auditing-program/
[3] https://www.iso.org/standard/80124.html

3.1.1 Standard flight scenario

Common to many Aviation Authorities, the most straight-forward operations at mine sites involve:

- One drone at a time, within visual line of sight (VLOS), during the daytime. This includes not flying behind structures, hillsides and not using goggles or binoculars.
- Lower than 120 m (400 ft) above ground level (AGL).
- Not allowing the cone of flying operations to be within 30 m of people or operating equipment.
- Not within restricted airspace, airfield boundaries, helicopter landing sites, temporary no-fly zones or within specified distances from airports with a control tower (e.g. 5.5 km in Australia, 4 km in Europe).

Although these criteria are straight-forward it is not uncommon for mine sites to struggle to deploy operations that are compliant with them. For example, in order to limit vibrations and extend flight time the best surveys avoid large altitude changes. Unfortunately, many open pit operations extend several hundred metres (or more) below the original ground surface. UAVs mapping pits can begin lower than 120 m AGL but breach the AGL limit as they fly across the pit. Similarly, it is not unusual for large, active mine sites to be adjacent to airfields with restricted airspace or active helicopter landing sites.

3.2 Exemplar Regulators and Compliance Requirements

In this section we outline regulatory requirements associated with two different approaches to UAV governance; EASA and CASA. The section is not intended to be a comprehensive description of all the steps required for companies to develop compliant operations. Instead, this section points to basic considerations relevant to UAV-HSI, as well as the regulatory logic associated with flying different types of UAV.

3.2.1 European Union Aviation Safety Authority

The body responsible for UAV regulation within the EU is the EASA. Therefore, the same rules apply to the different EASA member states, which include the 27 EU countries in addition to Iceland, Liechtenstein, Norway, and Switzerland. Although the EASA controls the broad regulations, the procedure for registration, insurance and permits are managed by the National Aviation Authority (NNA) for each nation state; noting that these are valid across the rest of EASA countries.

The EASA regulations have a risk-based approach, which means the requirements for flying a UAV increases with the risk of the mission. For these purposes, the EASA defines Classes and Categories summarised below and in Table 4:

C-Class Labels: These labels classify UAVs based on their weight and capabilities, organized between C0 and C6. UAVs sold in EASA countries are required to bear a class identification labels. If the UAV does not have a C-class label (i.e., legacy UAVs), they are subject to different operational limitations.

Categories: Three general categories been described for covering the risk-approach classification:

- **OPEN:** this low-risk operations involve UAV labels C0-C4 UAV, and specific scenarios (A1, A2, A3) related to flying close or far from people. It is important to identify in each scenario/sub-category the activities fall under, as the requirements may change.
- **SPECIFIC:** This category is for medium-risk operations, which are those outside the operational limitations laid out under the OPEN category. Examples include flying BVLOS and flying higher than 120m AGL. These operations require obtaining an

operational authorisation, however, there are some concessions that do not require such additional permitting:

- Submitting a declaration based on a standard scenario (STS). The EASA has created 2 specific standard scenarios (STS-01, STS-02). The UAV pilot will need a specific license to fly in the pre-defined STS.
- There is an operational certificate called LUC[4] which, if obtained, guarantees some privileges to its holder, including deploying operations in the specific category.

There is a further category (Certified), for the highest-risk operations such as air taxis, flights with cargo or passengers, which is not relevant to this White Paper.

If an operational authorisation is required, it is possible to use a Predefined Risk Assessment (PDRA), which are published risk assessments developed by EASA that are considered acceptable means of compliance. This approach allows applicants to quickly develop operator manuals etc. For operations not covered by an STS or a PDRA, a risk assessment known as SORA (Specific Operations Risk Assessment) is necessary.

The EASA also make a distinction between the UAV Operator and UAV Pilot:

- **UAV Operator** is any person or organisation who owns or rents UAVs (which must be registered with the corresponding NAA and obtain an ID/registration number that is placed on the UAV/UAVs.
- **UAV Pilot** is the person who conducts the UAV flights without necessarily owning the machine. That person must have completed the appropriate pilot training and exams and obtains the necessary licenses and certificates.

In addition, moving forward, the majority of UAVs will need to be equipped with a remote identification module (RID; easily purchased and attached if not supplied by the manufacturer). Such identification systems allow the public and authorities to identify and track the UAV both on the ground and while flying for security and transparency reasons. However, this approach is contentious and was widely criticised in the USA, although ultimately implemented there as well. An RID is not required in Australia presently.

[4] https://www.easa.europa.eu/en/domains/civil-drones-rpas/specific-category-civil-drones/light-uas-operator-certificate-luc

Table 4 - EASA. Scenarios definition: A1) Fly occasionally above people but not over assemblies of people; A2) Fly close to people; A3) Fly far from people. NNA: National Aviation Authority. In addition, starting from 1 January 2024, all drones operated in Specific Category need to be equipped with a remote identification system. STS are predefined scenarios that do not require an operational authorisation. Highlighted in red are scenarios most relevant to operation of UAV-HSI systems.

Cat	Scenario	Maximum Height (m AGL)	LOS	C-Class Label Max. Take off Mass	Drone Operator Registration	Minimum remote pilot competence	Authorization from the NNA (state of registration)
OPEN Low risk	A1 (+A3)	<120	VLOS	C0 (+ privately build or legacy < 250g) < 250 g	No, unless camera/sensor on board and UAV is not a toy.	Read carefully the user manual.	N
	A1 (+A3)	<120	VLOS	C1 < 900 g	Yes	Obtain a 'Proof of completion for online training' for A1/A3 (online training + exam)	N
	A2	<120	VLOS	C2 < 4 kg	Yes	Obtain a 'Remote pilot certificate of competency' for A2 (online training + exam, and practical self-training)	N
	A3	<120	VLOS	C3, C4 < 25 kg	Yes	Obtain a 'Proof of completion for online training' for A1/A3 (online training + exam)	N
Specific Mid risk	STS-01	<120 (urban areas)	VLOS	C5 < 25 kg	Yes	STS-01 (+ A1/A3)	N
	STS-02	<120 (not in urban areas)	BLOS	C6 < 25 kg	Yes	STS-02 (+ A1/A3)	N
	In any other low and medium risk operations not covered in the previous rows.				Yes		Out of standard scenarios (STS-01, STS-02), and if the operator does not have the **LUC**, an authorisation from the NNA is needed: - An operational authorisation following pre-defined risk assessment (PDRA). - An operational authorisation without a PDRA. In this case, applicants are required to conduct a risk assessment (SORA).

Table 5 - CASA Regulatory Framework for Deployment Drone Operations under Business Category (Excluding Recreational Category Due to Incompatibility with Mine Operations). RePL – Remote Pilot License. Highlighted in red are scenarios most relevant to operation of UAV-HSI systems.

Cat	Scenario	Maximum Height (m AGL)	Distance of a controlled aerodrome	LOS	Category Max. Take off Mass	Drone Registration/ Aviation Reference Number	Minimum remote pilot / operator competence	Flight Authorisation
Business (Remotely piloted aircraft - RPA)	Distance from people: 30 m (like scenario: A1/A3 in EASA)	<120	<5.5 km	VLOS	Micro < 250 grams	Y/Y	**UAV operator accreditation** Follow drone safety rules and standard operating conditions	N
	Distance from people: 30 m (like scenario: A1/A3 in EASA)	<120	<5.5 km	VLOS	Very small (**Sub-2 kg excluded category**) [250 grams - 2 kg]	Y/Y	**UAV operator accreditation** Follow drone safety rules and standard operating conditions	N
	Distance from people: 30 m (like scenario: A1/A3 in EASA)	<120	<5.5 km	VLOS	Small, (landowner/private landholder) **excluded category** [2 kg to 25 kg]	Y/Y	**UAV operator accreditation** Follow drone safety rules and standard operating conditions + keep the required operational records	N
	Distance from people: 30 m (like scenario: A1/A3 in EASA)	<120	<5.5 km	VLOS	Small [2 kg to 25 kg]	Y/Y	Obtain RePL: **Either sub 7kg RePL, or Sub 25kg RePL for multirotor.**	N
	Distance from people: 30 m (like scenario: A1/A3 in EASA)	<120	<5.5 km	VLOS	Medium, (landowner/private landholder) **excluded category** [25 kg - 150 kg]	Y/Y	Obtain RePL: **Sub 150kg RePL** (type specific ratings only)	N
	Distance from people: 30 m (like scenario: A1/A3 in EASA)	<120	<5.5 km	VLOS	Large > 150 kg	Y/Y	Obtain RePL: **> 150kg RePL** (type specific ratings only)	N
	In any other not covered in **Standard scenarios***				Small, Medium, Large	Y/Y	Corresponding **RePL (Remote Pilot)** and Corresponding **ReOC (Chief Pilot)**	Y*

3.2.2 Civil Aviation Safety Authority (Australia)

Following the same structure as an example for Australia, Table 5 summarizes the general scheme for permitting UAV operations for commercial purposes (UAV at mine sites) under the CASA.

The RePL certifications for UAS weighing less than 7 kg (Sub 7kg RePL) and less than 25 kg (Sub 25kg RePL) are issued for both the weight category and the UAV-type (e.g. multi-rotor RePL <25 kg for typical UAV-HSI systems; other UAV-types include single-rotor helicopter, fixed wing, VTOL, and airship). However, RePL certifications for UAVs weighing less than 150 kg (Sub 150kg RePL) and more than 150 kg are restricted to the specific UAV model being used. For example, obtaining a <150 kg RePL for a NOA Acecore does not permit the pilot to fly any other model of multirotor in the <150 kg class.

As outlined in Table 5, owner-operators of mine sites are able to qualify for the 'excluded category' for many types of UAV operations relevant to UAV-HSI. However, if flights are unable to meet the criteria for standard flight scenarios then the organisation requires a Remotely Piloted Aircraft Operators Certificate (ReOC)[5], involving the appointment of a Chief Pilot and Maintenance Officer, and the development of manuals and operational procedures. The Chief Pilot and Maintenance Officer can be the same individual but this is not recommended if multiple UAVs are part of the mine site's fleet. Similarly, all contract service providers should be operating with their own ReOC.

Flight authorizations are required for all situations not covered by standard scenarios (Table 5), and must be submitted to CASA by the Chief Pilot (ReOC holder). Additionally, the operation of the UAV deployment must be conducted by a Remote Pilot (RePL holder). If the Chief Pilot holds a RePL, they are permitted to operate the UAS.

The most common non-standard scenarios outlined in Table 6, which are relevant to UAV-HSI, tend to involve flying beyond visual line of sight (BVLOS) or above 120 m AGL, depending on the scale of the site that is to be surveyed and its topography.

[5] https://www.casa.gov.au/drones/get-your-operator-credentials/remotely-piloted-aircraft-operators-certificate#ApplyforaReOCthroughanindustrydelegate

Table 6 - CASA scenarios and their requirements for flights operating outside of the standard flight scenario.

<table>
<tr><th>Type of flight authorisation</th><th>Detail/Scenarios</th><th>Requirements</th></tr>
<tr><td rowspan="6">Area Approvals</td><td>Above 120 m AGL in controlled airspace</td><td rowspan="9">1. Application "Flight authorisation" form
2. RPAS operation manual and procedures
3. Risk and job safety assessment
4. Aeronautical radio qualifications
5. Flight plan</td></tr>
<tr><td>Above 120 m AGL in non-controlled airspace</td></tr>
<tr><td>Within 5.5 km of a controlled aerodrome (excluding military controlled aerodromes)</td></tr>
<tr><td>Above 120 m AGL within 3NM of a controlled aerodrome</td></tr>
<tr><td>Operate over a movement area of a controlled aerodrome</td></tr>
<tr><td>Operate over the approach or departure path of a runway of a controlled aerodrome (excluding military controlled aerodromes)</td></tr>
<tr><td rowspan="3">RPA Permissions</td><td>Operate over a movement area of non-controlled aerodrome</td></tr>
<tr><td>Operate above 120 m AGL within 3NM of a non-controlled aerodrome</td></tr>
<tr><td>Operate in R405 (Prohibited or restricted areas)</td></tr>
<tr><td rowspan="6">BVLOS</td><td>AU-STS1: near a vertical object(s) with a controlled ground environment</td><td rowspan="6">*All the above, plus:

1. Concept of operations (CONOPS)
2. AU-STS Applicant document according to the specific BVLOS scenario</td></tr>
<tr><td>AU-STS 2: near a vertical object(s) with a sparsely populated ground environment</td></tr>
<tr><td>AU-STS 4: in a remote area within 3 NM of a registered or certified non-controlled aerodrome</td></tr>
<tr><td>AU-STS 5: for emergency services or operators in response to natural disaster in sparsely populated areas or areas that are now considered evacuated</td></tr>
<tr><td>AU-STS 6: in remote Australian airspace (below 120 m AGL)</td></tr>
<tr><td>AU-STS 7: in remote Australian airspace (120 m AGL to 1500 m AMSL)</td></tr>
</table>

3.3 Radio Frequency Restrictions and the Aeronautical Operator Certificate (AROC)

UAV radio frequencies must comply with local regulations to ensure non-interference with other radio services or communication systems. When conducting UAV operations in a controlled airspace (within 5.5 km, or 3 nautical miles) an approval specifying the distance to the nearest aerodrome and the radio frequencies to be used is required. In contrast, in uncontrolled airspace, where there is no monitoring by a control tower, no additional approvals are required. However, the radio frequency used must align with the regulations specified by the relevant radio frequency authority for each nation (e.g. in Australia this is the Australian Communications and Media Authority). This point is most important for specialised UAVs in the <25 kg and <150 kg categories, where manufacturers sometimes provide radio controllers for the UAV that comply with USA or European legislation but not necessarily the legislation of other nations. For example, some UAVs use 868 MHz frequency, which is permitted in the EU but not Australia.

The Australian Communications and Media Authority has published the Australian Radiofrequency Spectrum Plan in the Federal Register of Legislation. The plan notably outlines radiofrequency spectrum management, the rules to follow for any services to execute in each frequency band, and the alignment with the International Telecommunication Union (ITU).

UAV operations that involve communication on an aviation air-band radio frequency must be conducted by a remote pilot (RePL holder) who is licensed or qualified with the Aeronautical Radio Operator Certificate (AROC). The certificate includes training and assessment, ensuring the remote pilot's capability to operate UAVs under these conditions. The AROC includes an 'english-language' test, to ensure radio operators and those receiving communications can understand each other.

4. Logistics

There are two important aspects of logistics for consideration relating to (1) the amount of equipment and field support required to run a mission, and (2) government or mine site regulations related to some of the equipment.

In addition to the components of a UAV-HSI system (see Section 2.1 - System Components and Typical Dimensions), the equipment required to support a campaign can lead to a moderately large inventory. When operating at remote locations around mine sites, typical support equipment includes in-field laptops (x2), pure sine wave generator with extension cables and fuel (3500W), RTK GPS/GNSS for surveying ground points (including potential locations of ground samples), gazebo, chairs and field table for computer set-up, handheld spectrometer for ground sampling (which may or may not require another laptop) and irradiance sensor.

The operation of the UAV-HSI requires a minimum of 2 persons, but regulatory and mine site requirements around spotters who have their eyes on the UAV during flight means that 3 persons may be actual minimum.

The size of equipment inventory and support personnel has several logistical implications:

- Two utes/pick-up trucks/4WD vehicles are necessary per deployment. Given that vehicle access in many operating mine areas is not permitted, and site vehicles are often in short supply, the transport arrangements around site need to be made well in advance.
- In mining nations like Australia, Chile, USA, and Canada, mine sites are often remote, and travel to them involves large (multi-day) travel by road. It is much more efficient to travel by air but this requires pre-shipping of batteries (batteries for UAV-HSI exceed air transport regulations and cannot be carried onboard airplanes), and the booking of large amounts of excess and oversize luggage in advance.

Critical regulatory considerations include:

- HSI imaging cameras have defense applications and some nations restrict the movement of these goods across their borders (for example, in Australia they are on the Defence and Strategic Goods List: category 6A002.b.2)[6]. This means that major mining companies, operating globally, cannot easily export/import a UAV-HSI system without the necessary permissions[7].
- LiPo batteries are considered dangerous goods. The power rating of UAV-HSI LiPo batteries means they have to move by road transport. Full disclosure must be made to the carrier before the consignment or carriage of them. In some cases, qualified packers are required to box up battery sets prior to transport, with documentation signed by the organiser of the survey, or the Chief Pilot if relevant.
- The use of generators and their fuel on mine sites have associated standard operating procedures and require specific risk assessments. Spill kits may be mandatory.

[6] https://www.defence.gov.au/business-industry/export/controls/export-controls/defence-strategic-goods-list

[7] https://www.defence.gov.au/business-industry/export/controls/assess-apply/how-apply

4.1 Site assessment, survey, and ground sampling strategy

The following is a checklist of steps to consider for a successful UAV-mounted HSI survey:

1. **Create a pre-field flight plan:** Develop a detailed flight plan that includes takeoff and landing zones, and flight paths, as well as consider all applicable emergency procedures. Avoid flying near or over roads and be aware of alternate UAV landing sites. The use of aerial photos and accurate digital elevation models are useful here and can be uploaded most flight planning software. For UAV-HSI the flight lines are should include the aspects below, which serve to increase the time a UAV-HSI system is required in the air. This needs to be accounted for when calculating the number of surveys and batteries required to complete a mission. The relative complexity of the flight lines is something that other personnel in the vicinity of an UAV survey should be aware of for safety considerations.
    a. Cross flight lines to help 'tie' the hyperspectral data
    b. Flight line overlap
    c. Adjacent survey overlap
    d. In-flight calibration flight line at the beginning of each survey.
2. **Permissions and landowner interactions**: In most cases, surveys for the resources sector will take place on land managed by the mine site. However, there are some examples where surveys will occur across land belonging to external owners, or have sensitivities associated with it, related to Traditional Owner/First Nations communities. Discussing flights and requesting access are important pre-field steps.
3. **Set-up considerations**: Ensure adequate signage, spotters and all necessary safety equipment (e.g. barriers) are in place, and mine site safety protocols are followed. Spotters are necessary to communicate with and periodically inform non-operational personnel of the activities at the site and to display signage.
4. **Start all works at any mining operation by conducting a site and risk assessment:** Identify potential hazards for UAV deployment (such as power lines, tall structures, and areas of high activity). Fly only in designated areas.
5. **Assess the on-the-day environmental conditions**: regularly monitor weather patterns and do not operate a UAV during adverse weather conditions such as high winds, heavy rain, lightning, or thick fog. It is critical to continuously assess sufficient visibility and cloud coverage for safe UAV operations and maintain a VLOS if required by regulations. The operating conditions to consider are:
    - Solar zenith angle (ideally lower than 70° and no greater than 80°)
    - Ambient temperatures
    - Wind speed, wind direction
    - Altitude
    - Ambient dust and dirt (rock surfaces and material for imaging are ideally dry)
    - Wildlife/birdlife
    - Presence of any magnetic infrastructure
    - Active air space
6. **Complete pre-flight checks** by inspecting the UAV to ensure all working components are in good condition. Ensure batteries are fully charged.
7. **Post-flight procedures** should include inspecting the UAV for any damage or issues after each flight. Afterward, safely transfer and store the collected data. Consider conducting a post-flight debrief to review the mission and identify any areas for improvement.
8. **Contingency planning** should include emergency landing procedures in case of equipment failure or other emergencies (e.g. bird attacks). Have protocols in place in case the UAV loses connection with the operator, especially 'geofencing' in and around mine sites.

One of the critical steps in constraining what is possible is the flight planning. Clearly, this is contingent on the UAV model and its flight duration (as highlighted in Section 2.1 - System Components and Typical Dimensions). The majority of HSI cameras tend to be integrated into UAVs with a MTOM just below 25kg (although this is changing as regulation makes it easier for pilots to fly 25-150 km platforms). Flight plans for UAVs with <25 kg MTOM should only be 10 mins (max.), with plenty of time allowed for descent and ascent (which tends to consume battery power quickly).

In terms of total time per flight, it is typical that the flight set-up, survey and post-flight checks take 30-45 minutes, before another flight can be readied.

Flight duration is also influenced by air temperature, wind speed, changes in terrain surface level, speed/ampere during battery charging, the take-off position and UAV's distance to the area of interest, fail-safe procedures, and wildlife. These factors increase the overall risk of the operation and it is not unknown for bad planning to result in UAV batteries to discharge while inflight.

A final aspect for consideration in UAV-HSI surveys is ground sampling for validation. This is not a step that will occur in every survey. Nonetheless, validation of the data against ground samples is best-practice. In situations where contract service providers are engaged to deliver hyperspectral data it should be requested as part of the survey program of work.

5. Conclusion and Future Considerations

The UAV-HSI systems discussed in this White Paper are interoperable technologies that have the potential to radically transform aspects of the mapping and monitoring needs that the resources sector faces (especially with regard to ore-waste tracking, exploration and environmental commitments).

Current commercially available systems are relatively complex, and subject to aviation standards and regulations that must be met. In this White Paper, we have provided an introduction to the standards most relevant to the types of UAVs that can carry HSI cameras. We have also outlined logistical considerations associated with obtaining and operating the equipment.

Future considerations include:

Regulatory development – As described in Section 3 (Compliance, Standards, and Safety), regulations are continually adapting in order to keep abreast of rapid changes in UAV technology and its applications. The direction of regulatory change appears to be ensuring more complex flights can occur with less need for special accreditation and approvals, while at the same time minimising risk. As part of these changes, it is likely the near future will require RIDs as a global standard (not just Europe and USA). Larger machines, such as those used by UAV-HSI platforms may require rotor guards and ballistic parachutes.

Onboard data processing and real-time capabilities - As described in Section 2.2.4 (Other considerations – data management), UAV-HSI systems produce large amounts of data. This is logistically challenging for resources sector professionals to manage, as they do not always have access to the necessary compute to handle such data. A key future development is the automated processing of data, so that UAV-HSI can deliver real-time or near real-time information to the resources sector, to reduce the logistical challenge that industry professionals face in data processing, interpretation and management. This aspect of future development is being addressed by the M4Mining research consortium.

Data security, cloud storage & automated backup - As described in Section 2.2.4 (Other considerations – data management), UAV-HSI systems produce large amounts of data. With the advent of affordable and relatively reliable communications networks in remote areas, like Starlink, it is possible to transfer data moderately quickly to cloud-based archives. Nonetheless, UAV-HSI data can be in the order of terabytes, which is currently too large for easy transfer. Future development is required to establish the protocols and automated services for upload of UAV-HSI data, to secure cloud-based storage (e.g. perhaps overnight). This problem has already been solved for other technologies and we consider this development to be achievable.

Data integration and interoperability are provided through data processing and visualisation tools (e.g., Google Earth Engine, AWS Lambda) for analysing and interpreting hyperspectral and LiDAR data. These tools also support various data formats that are extensively used in remote sensing and geospatial analysis.

Remote operations centres (ROCs) – As described in Section 4 (Logistics), the amount of equipment and field support required for commercially available UAV-HSI is moderately large. The logistical challenges (and associated costs) can be significantly reduced by adapting UAV-HSI into emerging drone-in-a-box solutions, with pilots able to conduct surveys from off-site ROCs. This aspect of future development would require battery recharge, satellite-based data upload and communications, and on-box irradiance sensors amongst other things. It is nevertheless the most important development for providing a packaged, easily accessible solution that the resources sector can deploy with minimum disruption.

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