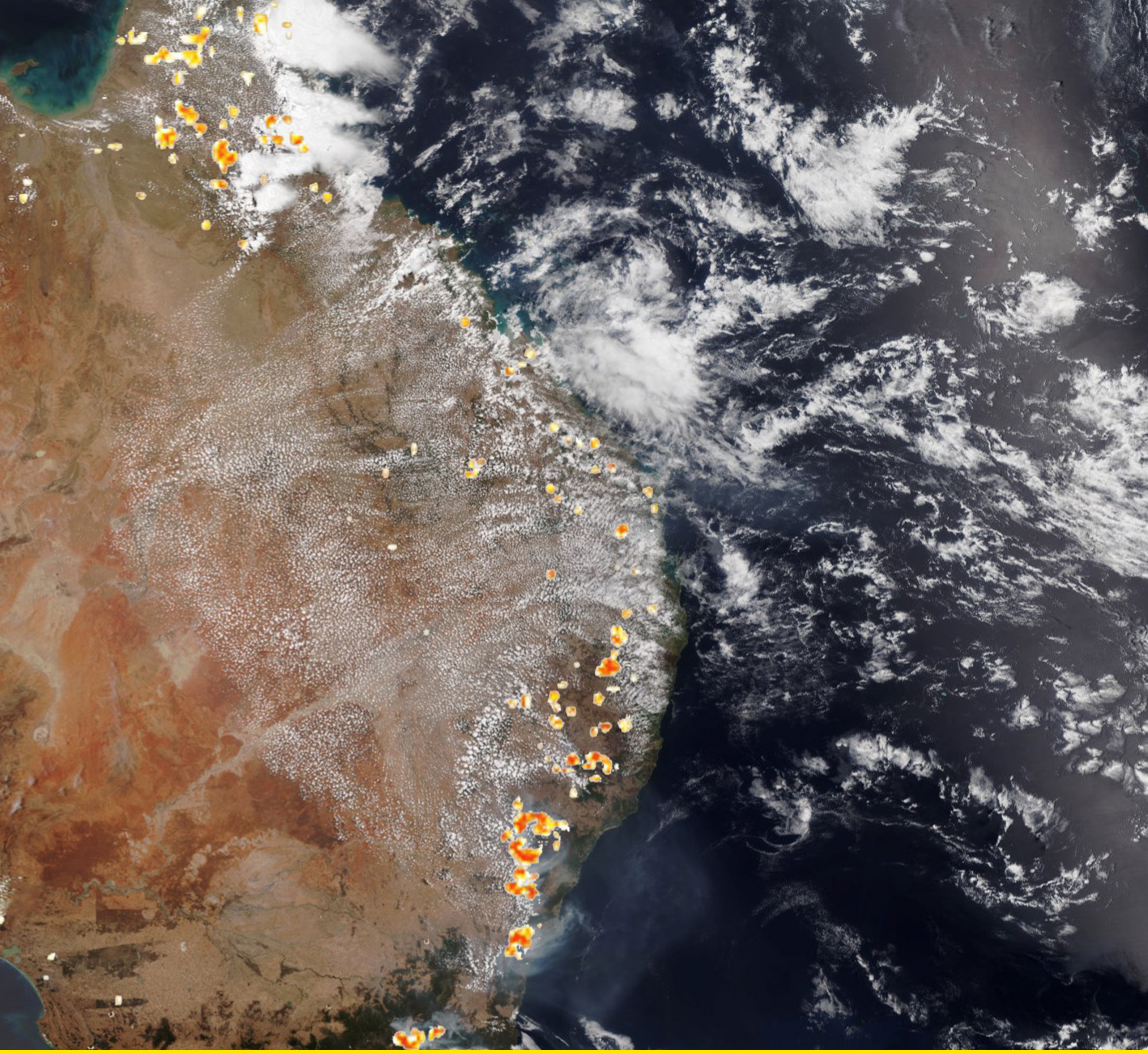


OzFuel Phase A Study Report

Space-based Australian Forest Fuel Flammability Monitoring

space.unsw.adfa.edu.au

UNSW CANBERRA | Space

UNSW CANBERRA | Space

OzFuel Phase A Study Report:
Space-based Australian Forest Fuel Flammability Monitoring

© The University of New South Wales, 2022.
Published by UNSW Canberra Space, November 2022.

The material in this publication is licensed under a Creative Commons Attribution - 4.0 International licence, with the exception of:
- any third party material
- any trademarks, and
- any images or photographs.

Wherever a third party holds copyright in this material, the copyright remains with that party. Their permission may be required to use the material. Please contact them directly.

More information on this CC BY license is set out at the Creative Commons Website: creativecommons.org/licenses/by/4.0/

Enquiries | Any enquiries regarding this report may be addressed to:
UNSW Canberra Space
Director, Prof. Russell Boyce
PO BOX 7916
CANBERRA BC
ACT 2610
P +61 2 5114 5594
E space@adfa.edu.au

Attribution | Use of all or part of this publication must include the following attribution: © The University of New South Wales, 2022. Published by UNSW Canberra Space, November 2022.

Cover Image: Courtesy of NOAA, 2019

Citation | UNSW Canberra Space (2022). OzFuel Phase A Study Report: Space-based Australian Forest Fuel Flammability Monitoring. Available at: space.unsw.adfa.edu.au
DOI: 10.26190/k3sb-6p54

Disclaimer | By accessing or using this publication, you agree to the following: This publication is not legal or professional advice. Persons rely upon this publication entirely at their own risk and must take responsibility for assessing the relevance and accuracy of the information in relation to their particular circumstances.

Acknowledgment | The OzFuel satellite mission is a flagship project of the Australian National University Institute for Space (InSpace).

This Phase A study was made possible by the financial contribution of the SmartSat CRC (Project 3-24). We acknowledge the support of the Australian National University (ANU), the ANU Institute for Space (InSpace), and the contributions made by all participants.

The Australian National University and the University of New South Wales are core partners of the SmartSat CRC.

Australian National
Concurrent Design Facility

OzFuel Phase A Study Report
Space-based Australian Forest Fuel Flammability Monitoring

Industry participants:

Executive Brief

- This work reports on the 14th concurrent engineering study conducted at UNSW Canberra Space Australian National Concurrent Design Facility (ANCDF) during a 5-day workshop on 21-25 February 2022.
- Australia relies on foreign satellite imagery and measurements not optimised for monitoring Australian bushfire fuel flammability, leading to fires in the Australian landscape. The 2020 Royal Commission into National Natural Disasters highlights the need for whole-of-continent visibility of vegetative fuel load in terms of quantity and moisture content [RD-1].
- The Australian National University (ANU) Institute for Space (InSpace) previously developed a Pre-Phase A Report for Geoscience Australia and CSIRO in support of their contribution to Australia's Satellite Cross-Calibration Radiometer (SCR) and AquaWatch Australia missions. That report described the OzFuel mission, its science objectives and a set of mission requirements and payload/instrument performance requirements to meet the mission objectives [RD-2].

- OzFuel is a Pathfinder Earth Observation (EO) mission designed to monitor vegetative fuel flammability across Australia. It aims to provide:
    - A satellite system that monitors fire fuel flammability in the Australian context at an optimal spatial, temporal, spectral and radiometric resolution.
    - A capability enabling the future development of a fully operational satellite constellation for bushfire prediction, prevention, mitigation, and resilience.
    - Observational data to support the government, frontline emergency service organisations and communities in improving bushfire situational awareness and preparedness.
    - Global fuel hazard spatial data analysis techniques to augment domestic and international commercial and government-led fire detection initiatives.
    - A pathway to develop the Australian space sector, including manufacturing, assembly, integration, and testing (MAIT) activities.
    - A de-risking opportunity in the development of the SCR and AquaWatch Australia programmes.
- The current Phase A study was performed in collaboration with science and engineering personnel from the ANU, Skykraft Pty. Ltd., University of Melbourne Space Laboratory (MSL), Spiral Blue, Geoscience Australia, and UNSW Canberra Space. This Phase A study has achieved the following:

    - Identified several development risks that need mitigation but found the OzFuel mission technically and programmatically feasible. While no commercial off-the-shelf (COTS) component option exists for the whole system, the complexity of the mission is not beyond the current capabilities of the global and Australian space sectors.

    - Determined the value of the mission to Australia and found that crucial partnerships would be maximised by aligning to the timelines of other missions, such as SCR.

Contents

Table of Figures

Table of Tables

List of acronyms and abbreviations

Abbreviation	Description / meaning
18 SDS	18th Space Defence Squadron
ACT	Australian Capital Territory
ADC	Analog-Digital Converter
ADCS	Attitude Determination and Control Subsystem
AIT	Assembly, Integration, and Test
ANCDF	Australian National Concurrent Design Facility
ANGSTT	Australian National Ground Segment Technical Team
ANU	Australian National University
APE	Absolute Pointing Error
APEC	Asia-Pacific Economic Cooperation
APK	Absolute Pointing Knowledge
ASA	Australian Space Agency
AUD	Australian Dollar
AUS	Australian
AWS	Amazon Web Services
CARD4L	CEOS Analysis Ready Data for Land
CC BY	Creative Commons, Attribution
CEOS	Committee on Earth Observation Satellites
CLARREO	Climate Absolute Radiance and Refractivity Observatory
CMP	Configuration Management Plan
CNES	Centre National d'Etudes Spatiales
CoM	Centre of Mass
ConOps	Concept of Operations
COTS	Commercial Off-the-Shelf
CRC	Cooperative Research Centre
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CSS	Coarse Sun Sensor
DDVP	Design, Development and Verification Plan
DFL	Dry Fuel Load
eAPD	Electron Avalanche Photodiode
EHS	Earth Horizon sensor
EM	Engineering Model
EMC	Electromagnetic Compatibility
EMI	Electromagnetic Interference
EO	Earth Observation
EPS	Electrical Power Subsystem
ESA	European Space Agency
ESD	Electro-Static Discharge
f/#	F number or aperture number
FEE	Front End Electronics
FM	Flight Model
FMC	Fuel Moisture Content
FPA	Focal Plane Array
FPGA	Field Programmable Gate Array
FPS	Frames Per Second
FRR	Flight Readiness Review
FTE	Full-Time Equivalent
GA	Geoscience Australia
GB	Gigabyte
GDP	Gross Domestic Product
GPS	Global Positioning System
GS	Ground Station or Ground Segment
GSD	Ground Sampling Distance
GSE	Ground Support Equipment
ICD	Interface Control Document
IR	Infrared
IRF	Impulse Response Function

Abbreviation	**Description / meaning**
Isp	Specific impulse
L0/1/2/3/4	Level 0/1/2/3/4 (data products)
LEO	Low Earth Orbit
LEOP	Launch and Early Orbit Phase
LOS	Line Of Sight
LSP	Launch Service Provider
LTAN	Local Time of Ascending Node
LV	Launch Vehicle
MB	Megabyte
MCR	Mission Concept Review
MCT	Mercury Cadmium Telluride
MOC	Mission Operations Centre
MoI	Moment of Inertia
MSL	Melbourne Space Laboratory
MTF	Modulation Transfer Function
N/A	Not Applicable
NASA	National Aeronautics and Space Administration
NEdL	Noise Equivalent change in radiance
NSTF	National Space Test Facility
NVM	Non-Volatile Memory
OBC	On-board computer
PDR	Preliminary Design Review
PF	Pathfinder
PFM	Proto-flight model
PICS	Pseudo invariant calibration sites
PL	Payload
PMM	Payload Management Module
RF	Radio frequency
RMP	Risk Management Plan
ROI	Region Of Interest
ROM	Rough Order of Magnitude
SCR	Satellite Cross-calibration Radiometer
SEMP	System Engineering Management Plan
SI	Systeme International
SM	Structural Model
SNR	Signal-to-Noise Ratio
SRR	System Requirements Review
SSO	Sun-Synchronous Orbit
STM	Structure and Thermal Model
SWIR	Short-Wave Infrared
TBC	To Be Confirmed
TBD	To Be Determined
TDI	Time Delay Integration
TheMIS	Thermal Management Integrated System
TM	Thermal Model
TOA	Top Of Atmosphere
TRL	Technology Readiness Level
TT&C	Telemetry, Tracking, and Command
UK	United Kingdom
UNSW	University of New South Wales
US	United States
USD	US Dollar
USGS	United States Geological Survey
WBS	Work Breakdown Structure

Reference Documents

[RD-1] Report/ Royal Commission into National Natural Disasters Arrangements (2020), https://nla.gov.au/nla.cat-vn8555232

[RD-2] ANU Institute for Space (2021), OzFuel Pre-Phase A Study: Australian Forest Fuel Monitoring from Space, August 2021; inspace.anu.edu.au/activity/missions/ozfuel

1 Introduction

The Australian National University (ANU) and Optus have joined to create a Bushfire Research Centre of Excellence, pursuing various short, medium, and long-term objectives to help detect and extinguish bushfires shortly after ignition[1]. Paramount to this programme is a microsatellite mission named OzFuel, a flagship mission of the ANU Institute for Space. The OzFuel satellite will host an infrared sensor to measure the leaf-level traits that influence eucalypt forest fuel flammability; we define flammability as a measure of a substance's susceptibility to ignition[2]. OzFuel would enable near-real-time analysis and monitoring of the vegetative conditions that create bushfires if deployed in a Low Earth Orbit (LEO) constellation.

The OzFuel mission aims to monitor vegetative fuel flammability with a particular focus on Australian eucalypt forests. This aim is achieved via satellite remote sensing to deliver whole-of-continent forest fuel flammability data at the optimum spatial, temporal, and spectral resolution. Initially conceptualised as a Pathfinder to demonstrate the capability, the migration to a national environmental monitoring constellation will improve area coverage and revisit time. The OzFuel mission aims to provide critical bushfire Earth observation data to support the government, frontline organisations and communities for enhanced bushfire situational awareness and preparedness.

In addition, **OzFuel would secure Australian access to EO data** by:

- signalling the Australian intent to contribute to the global Earth observing system,
- strengthening relationships with other space-faring nations, and
- domestically substantiating the goals set out in the Australian Civil Space Strategy 2019-2028[2].

OzFuel provides an opportunity for developing the capability of the Australian space sector across manufacturing, assembly, integration, and testing disciplines, as well as mission operations.

The OzFuel mission has a defined set of preliminary data user needs and some derived mission and space segment requirements, including those at the imaging payload level. Further efforts need to be expended to finalise these user and mission requirements before a detailed conceptual design of the space segment, ground segment, and mission operation segment can be completed.

The current OzFuel mission concept is **feasible** regarding existing technical capability within Australia and the global space community. In addition, the risk analysis carried out in this study identified suitable mitigations against the highest-ranked risks. With these risk management provisions implemented, the overall programme risk profile is comparable to international small satellite missions.

UNSW Canberra Space conducted this study in collaboration with and on behalf of the ANU Institute for Space and Geoscience Australia. It applied a concurrent engineering methodology closely aligned with NASA's systems engineering[3] approach to derive a space mission feasibility assessment and an initial cost estimation. The core study team comprised 28 science and engineering personnel.

The results of this work **will inform the Australian Government Satellite Earth Observation Roadmap** ("the Roadmap") released in 2021 by the Australian Space Agency, the Bureau of Meteorology, CSIRO, the Department of Defence and Geoscience Australia in close partnership with the Australian Earth observation community.

---

[1] ANU, 01/10/2020, ANU-Optus Bushfire Research Centre of Excellence, https://www.anu.edu.au/news/all-news/anu-optus-bushfire-research-centre-of-excellence

[2] https://www.afac.com.au/docs/default-source/doctrine/bushfire-terminology.pdf

[3] Kapurch, S. J. (Ed.). (2010). NASA systems engineering handbook. Diane Publishing. Available at: https://www.nasa.gov/sites/default/files/atoms/files/nasa_systems_engineering_handbook_0.pdf

2 Study context

The ANCDF is an above-the-line research sector-operated national asset that complements the National Spacecraft Test Facilities (NSTF) operated by the Australian National University.

UNSW Canberra established the ANCDF with financial assistance from the ACT government and technical assistance from the French Space Agency (CNES). It is a concurrent engineering design facility in which space mission feasibility studies can be performed in an immersive environment with space engineers and the customer/user sitting together to develop and test the viability of proposed missions.

Fourteen studies have been conducted in the ANCDF in recent years. These studies include the NICSAT study for the Office of National Intelligence with the Australian National Intelligence Community and the Lamanon intelligent EO satellite study with CNES and Airbus.

A series of studies were conducted in 2021 to support the development of the Australian Government Satellite Earth Observation Roadmap, Pre-Phase A study for meteorology and disasters instrumentation (Bureau of Meteorology)

- Pre-Phase A study for AquaWatch (CSIRO)
- Phase A study for the SCR series (Geoscience Australia)

The final reports for these studies elaborated on preliminary technical designs and analyses of various satellite architectures and subsystems to deliver the required capabilities (https://www.unsw.adfa.edu.au/our-research/facilities/ancdf).

This study is consistent with NASA's definition of a phase A design study[4].

Table 1 NASA's definition of space mission phase A

Phase A	Concept and Technology Development
Purpose	To determine the feasibility and desirability of a suggested new system and establish an initial baseline compatibility with strategic plans. Develop final mission concept, system-level requirements, needed system technology developments, and program/project technical management plans.
Typical outcomes	System concept definition in the form of simulations, analysis, engineering models and mock-ups, and trade study definition

https://www.nasa.gov/seh/3-4-project-phase-a-concept-and-technology-development

There are two exceptions to the adherence to the NASA standard:

1. Formal Pre-Phase A design reviews, including Mission Concept Review (MCR) and System Requirements Review (SRR), have **not** been undertaken; and
2. Baseline plans outside this document have **not** been generated. In future phases of the program, these could include, as a minimum (and in keeping with a Class D program): a Program Management Plan (PMP), Work Breakdown Structure (WBS) and Product Tree, Systems Engineering Management Plan (SEMP), Risk Management Plan (RMP), Master Schedule, Design, Development and Verification/AIT Plan (DDVP), Configuration Management Plan (CMP), Component Control Plan, Deliverable Items List (includes product hardware and software deliverables), Deliverable Document List (includes contract regulated reports, plans, data packages, analyses, models, lists of components, parts, processes and materials, engineering documents, schedules, specifications, manuals, drawings, diagrams, Interface Control Documents, (ICD), Concept of Operations (ConOps) documents, processes and procedures), and Customer Furnished Item List.

---

[4] NASA (2016), Expanded Guidance for NASA Systems Engineering, Volume 1: Systems Engineering Practices, NASA/SP-2016-6105-SUPPL, Washington D.C., USA

These departures from NASA's standard are due to several competing factors, which we attempt to balance in this document:

- Australia has not undertaken a civilian government satellite development mission in several decades and, as such, does not have any current satellite development standards
- Australia recognises the benefits of Space 2.0 concepts and is not ready to fully accept all aspects of existing standards like NASA's or ESA's; and
- The OzFuel mission and an Australian civilian government satellite development body are currently conceptual and unfunded.

The current OzFuel mission concept is technologically **feasible** and could be developed by leveraging the existing technical capability within Australia and the global space community. The costing analysis on the perceived work and expenses show that the mission as envisioned would cost approximately $9 M AUD. Alternative spacecraft platform providers (other than Skykraft) and launch providers may lower OzFuel's mission cost; but such options have not been extensively explored and are beyond the scope of this study.

However, the study found that additional analysis and refinement of the mission's concept of operations, user and mission level requirements will be needed before detailed trade studies can be performed. These refinements will guide the development of system and subsystem requirements and ultimately lead to a robust system design that will inform a Phase B development effort.

The study considered the development of a single spacecraft as a dedicated Pathfinder, which would validate operations and mitigate the risk of new subsystems. It would also validate aspects of a fully operational constellation of spacecraft, providing higher revisit rates and an improved fuel flammability monitoring capability.

3 Background

Satellite Earth observations contribute over $5 billion to Australia's annual GDP[5] through applications in industries as diverse as weather prediction, agricultural production, climate monitoring, climate adaptation, mining and extractive technologies, financial services, infrastructure development, environmental monitoring, and disaster management. Government agencies that depend on such services include Geoscience Australia, CSIRO, the Bureau of Meteorology, and various Defence agencies.

In 2019, a report commissioned by the Australian Government[6] found that combined Earth and marine observation is worth USD 29 billion to Australia and USD 543 billion to the Asia-Pacific Economic Cooperation (APEC) economies each year. The value to Australia is forecast to increase to USD 66.5 billion (approx. $96 billion AUD) by 2030. Having no EO satellites of its own, Australia relies on international partnerships with satellite operators and space agencies to meet its Earth observation needs.

These global partnerships are built on a foundation of bi- and multi-lateral agreements and a long-standing practice of collaboration in critical areas such as data standards and processing, curation and distribution, and calibration and validation. Each component forms a crucial link in the supply chain that enables Australia to realise satellite data's full economic and scientific value.

The climate crisis over the past decade culminated in unprecedented 2019/2020 Australian bushfire conditions that were more catastrophic than expected or modelled[7]. The risk of larger and more frequent mega-fires will only increase in future years[8]. Allocating further ground resources to suppress fires is highly costly and dangerous. It needs to be augmented with more effective prediction, prevention and mitigation strategies before an unforeseen ignition event burns out of control[9].

One of the most crucial aspects of fire prevention is understanding the vegetative fuel traits that make eucalyptus leaves more or less flammable at any given time. The 2020 Royal Commission into National Natural Disasters highlights the need for whole-of-continent visibility of the vegetative fuel data. These data include fuel load (how much fuel there is) and fuel condition (how much water, structural carbohydrates and volatile organic and other compounds are in eucalypt leaves). To retrieve information on fuel conditions, Australia relies on foreign satellite data that is not optimised for measuring our unique bush landscape. The growing need for sovereign satellites to remotely sense Australia's unique vegetation has been supported by recommendations from the government, agencies, industry, and research institutions.

The OzFuel mission aims to monitor vegetative fuel conditions in eucalypt forests via satellite remote sensing to deliver whole-of-continent forest fuel flammability information at the optimum spatial, temporal, and spectral resolution. Conceptualized as a Pathfinder to a national environmental monitoring constellation, the OzFuel mission will provide critical bushfire Earth observation data to support the government, frontline organizations and communities for enhanced bushfire situational awareness and preparedness.

OzFuel is developed in parallel with CHICO, a hyperspectral imager for water quality monitoring (ANU and partners). While each mission has unique requirements, both serve as stepping stones to de-risk critical sovereign capabilities and enable fully operational national satellite missions.

---

[5] 2015. The Value of Earth Observations from Space to Australia. ACIL Allen Consulting Pty. Ltd.

[6] 2020. Current and future value of earth and marine observing to the Asia-Pacific region. Nous Group for the Australian Government.

[7] The 2019/2020 mega-fires exposed Australian ecosystems to an unprecedented extent of high-severity fire - IOPscience
Luke Collins *et al* 2021 *Environ. Res. Lett.* 16 044029

[8] Cattau M E, Wessman C, Mahood A and Balch J K 2020 Anthropogenic and lightning-started fires are becoming larger and more frequent over a longer season length in the USA *Global Ecol. Biogeogr.* 29 668–81

[9] Yebra, M., Barnes, N., Bryant, C., Cary, G. J., Durrani, S., Lee, J.-U., Lindenmayer, D., Mahony, R., Prinsley, R., Ryan, P., Sharp, R., Stocks, M., Tridgell, A., & Zhou, X. (2021). An integrated system to protect Australia from catastrophic bushfires. The Australian Journal of Emergency Management, 36(4), 20–22. https://search.informit.org/doi/10.3316/informit.193907664320405

4 Mission overview

This chapter provides a high-level overview of the mission, its scientific, policy and industry benefits and how it relates to other existing or planned international Earth observation satellite missions.

4.1 OzFuel mission concept summary

It has been established that the spectral and radiometric resolution in existing satellite data should be tailored for monitoring fuel conditions in Australia's eucalypt-dominant bushland [RD-2]. The OzFuel mission aims to monitor vegetative fuel conditions in eucalypt forests via satellite remote sensing to deliver whole-of-continent forest fuel flammability data at the optimum spatial, temporal, and spectral resolution. It will provide critical bushfire observation data to support the government, frontline organisations and communities for enhanced bushfire situational awareness and preparedness.

The mission proposes a program of work beginning with the OzFuel demonstrator mission. This mission will deliver a bespoke sensor system to achieve appropriate ground resolution and signal-to-noise ratio (SNR) in four short-wave infrared (SWIR) bands dedicated to monitoring the leaf-level traits that determine fuel flammability in Australian eucalypt forests. Knowing how much water, structural carbohydrates, and volatile organic and other compounds are in eucalypt leaves allows an assessment of fuel flammability and the potential severity of bushfires.

OzFuel is being developed concurrently with the CHICO instrument (ANU), a hyperspectral imager for water quality monitoring (AquaWatch mission; ANU, CSIRO, and partners). While each mission has unique user requirements, both serve as a staged series of development missions to de-risk critical sovereign capabilities, such as SCR, and enable larger, fully operational national satellite missions.

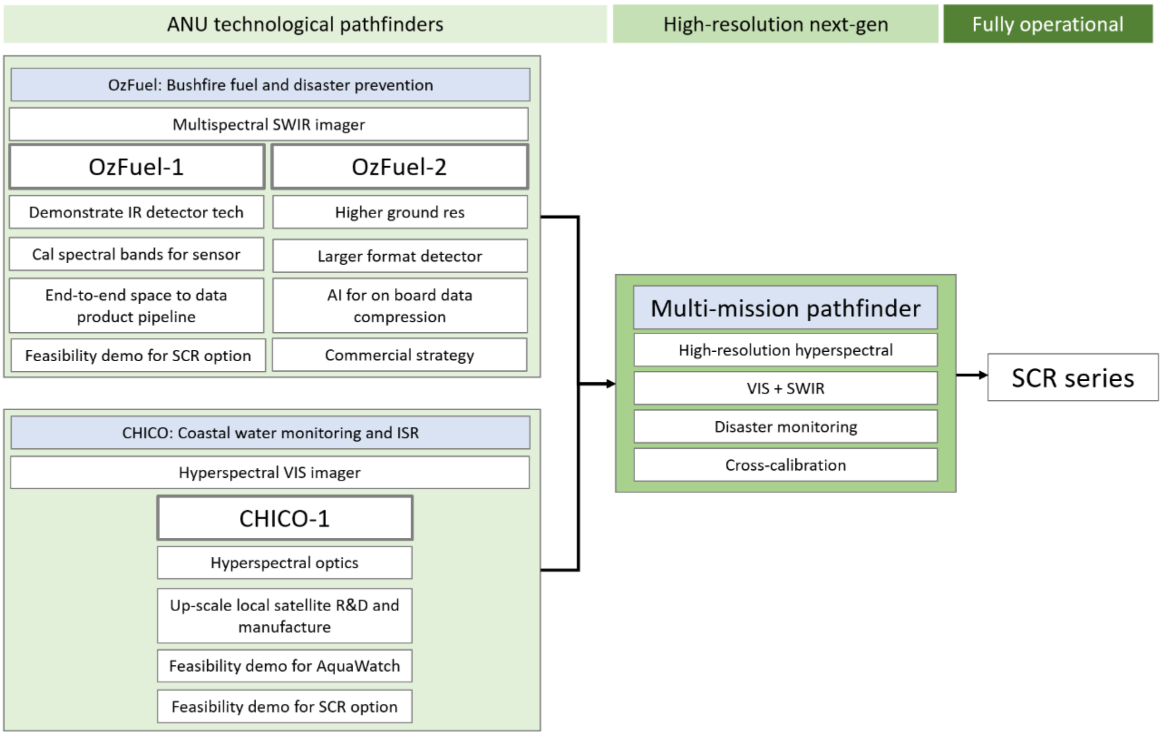
The first OzFuel satellite is envisioned as a microsatellite (<50 kg) operating a 4-band SWIR sensor in a low Earth orbit (LEO). The orbit would be selected to enable the demonstrator to image calibration sites in Australia at a revisit rate of approximately 21 days. An orbit for a constellation would be chosen to provide a 3-5 day revisit rate and possibly provide coincident observations with highly-calibrated optical missions such as Landsat 8 and Sentinel 2, as well as leverage the capability brought by the Australian SCR series.

The envisioned fully operational constellation consists of several OzFuel satellites and a network of ground stations supporting operations and data downlink. In the Pathfinder mission, sensor L0 data is received at the ground station and transmitted to the mission scientific director at ANU for processing and evaluation.

The mission development architecture is depicted schematically in

Figure 1.

Figure 1 OzFuel mission development architecture[10]



4.2 Benefits

The OzFuel mission would provide scientific, policy and industry benefits. These are outlined in the following sections.

4.2.1 Scientific benefits

The OzFuel programme will allow the development of space-proven Australian infrared (IR) focal plane assembly (FPA) technology for national and commercial small-satellite missions. It will include high-speed and low-noise front-end electronics for sensor readout and data processing, as well as domestically developed and qualified space optical systems.

The data collected by OzFuel will also further the understanding of the relationship between the different traits of Eucalypt leaves and forest flammability.

4.2.2 Policy benefits

The OzFuel programme will create opportunities to partner on domestic and international fire monitoring and prevention missions. These opportunities provide a concrete pathway for local stakeholders to access mentorship and support that can help develop their capability and bolster an international profile. The programme would also allow Australia to contribute geospatial data to national and international fuel characterisation and fire detection initiatives, thereby enhancing the strength of these relationships while providing users with unique data for better bushfire situational awareness and preparedness.

---

[10] ANU Institute for Space (2021), OzFuel Pre-Phase A Study: Australian Forest Fuel Monitoring from Space, August 2021; inspace.anu.edu.au/activity/missions/ozfuel

4.2.3 Industry benefits

The OzFuel programme aims to promote the growth of the Australian space industry by demonstrating domestic capabilities in mission design and operations for space-based bushfire prevention, mitigation, and resilience.

4.3 Related missions

This section provides an overview of current and planned missions related to the OzFuel programme.

4.3.1 AquaWatch Australia – CSIRO and SmartSat CRC

AquaWatch Australia is a program to monitor inland and coastal water quality from the ground and from space combining sensor data to create information products for the benefit of various downstream users. A secondary goal of the program is to grow Australia's space industry[11]. The programme is currently in pre-phase A and is led by CSIRO and SmartSat CRC, with a range of government and industry partners[12]. The primary purpose of this phase is to identify user needs and determine the technical and programmatic feasibility of the whole program.

4.3.2 Satellite Cross Calibration Radiometer – Geoscience Australia

The Satellite Cross Calibration Radiometer (SCR) mission will provide another foundational system to achieve the higher accuracy and stable observations needed to reduce the radiometric uncertainties in EO data products. Specifically, SCR will be a hyperspectral imaging spectrometer providing improved spatial resolution compared to CLARREO Pathfinder (from 150 m to less than 100 m) and a radiometric uncertainty of 3% on-orbit, which can then be transferred to other Earth observation platforms.

SCR's primary mission is to provide the gold standard for radiometric cross-calibration among commercial and government EO data sets. Ideally, SCR would be ready before or shortly after the deployment of CLARREO Pathfinder.

4.3.3 Australia as a global test track for EO calibration and validation

Building on Australia's reputation in satellite Earth observation calibration and validation, there are active discussions across Australia about a proposal to position Australia as the global satellite test track for EO calibration and validation. This strategy has three components:

1. A comprehensive, operational network of calibration and validation facilities across Australia.
2. A suite of tools to enable global satellite operators to use the infrastructure.
3. A series of SCRs to provide improved accuracy and consistency between optical satellites.

Operational planning for on-orbit calibration of the OzFuel sensor should take advantage of these initiatives where possible.

---

[11] SmartSat CRC, not dated, AquaWatch Australia, https://smartsatcrc.com/app/uploads/SmartSat_FactSheet_AquaWatch-FINAL.pdf, accessed 12/02/2021

[12] CSIRO, 2020, Space technology set to boost national water quality management, https://www.csiro.au/en/News/News-releases/2020/Space-technology-set-to-boost-national-water-quality-management, accessed, 12/02/2021

4.4 Pre-Phase A study summary

ANU's OzFuel team published a report describing the mission concept of operations (ConOps), upper-level requirements, and the payload/instrument performance requirements based on an initial set of OzFuel science objectives [RD-2]. The following sections describe how this information was used as the basis for the analysis performed in this ANCDF study.

A core part of any ANCDF activity consists of formulating mission objectives from the customer's perspective and deriving mission and system requirements to fulfil those objectives.

The following sets of requirement specifications have been defined at this stage:

- **Mission objectives** as stated by the customer
- **Mission requirements** as derived from the mission objectives and previous technical analyses
- **Space segment performance requirements** as derived from the observational requirements/specification and includes both instrument and platform requirements
- **Specify areas in which the Pathfinder mission may deviate from the fully operational mission** consisting of a spacecraft constellation

There are several performance drivers for the OzFuel mission. During the study, the following observations were made:

- Spatial resolution or ground sample distance (GSD) of 50-60 m is ideal.
- Revisit time is not critical for the Pathfinder mission, with up to 21 days deemed acceptable for imaging operations over specific regions of interest. However, revisit times on the order of one week or less would be preferable for a fully operational constellation of two or more spacecraft.
- A polar Sun-Synchronous Orbit (SSO) with a local time of ascending node (LTAN) between 12:00 and 14:00 are acceptable for the Pathfinder. Ideally, forest fuel is monitored in the early afternoon hours when heat stress and the potential for ignition are highest.
- Observation from late spring through early autumn is essential, implying that launch and commissioning activities should occur in late autumn/early winter.

Mission architecture choices have been made regarding the space segment and sensor development and are described in the references noted in [RD-2]:

- The OzFuel sensor will be designed around the Leonardo SAPHIRA eAPD detector (256 x 320 pixels of 24 µm) and the ANU-developed Rosella front-end electronics module.
- OzFuel will adopt the thermal control system developed by MSL, which employs the TheMIS thermal control module coupled with the Thales LSF9987 cryogenic cooler. TheMIS was developed for MSL's SpIRIT mission.
- ANU will provide the OzFuel optical system. It will be designed to provide diffraction-limited performance for a larger Leonardo SWIR detector array (512 x 512 pixels of 24 µm). This will allow reusing the same optical system in subsequent missions while expanding the monitoring capability.
- Skykraft will supply the bus (Block 2 platform) and provide launch services for SSO insertion. Leveraging Skykraft technology will reduce non-recurring engineering (NRE) costs to develop a custom platform for the OzFuel mission.
- Lessons learnt from The University of Melbourne's SpIRIT mission (2022) will retire risks associated with the TheMIS cryocooler.

4.5 Concept of operations

This section summarises the ConOps and ground segment requirements, supplemented by the previously performed analyses by the customer consortium (ANU, Skykraft and the MSL) and conclusions reached during this study.

4.5.1 In-orbit operations

At this stage, the OzFuel mission ConOps consists of two default image collection scenarios:

- **Pathfinder mission: An orbit that allows initial science data to be collected by the Pathfinder mission.** The Pathfinder default imaging mode is to acquire imagery during observation windows encompassing the National Arboretum site in Canberra, where designated field validation areas are established.
- **Operational mission: An orbit that maximises coincident observation opportunities with a selected reference mission**. The full operational capability mission default mode is to image land cover over Australia, satisfying the area collection and revisit time requirements of the constellation mission. Depending on science needs and programmatic aspects, the selected reference mission could be NASA's Landsat, ESA's Sentinel, or ASA's SCR.

The selection of a suitable orbit should also compare these two generic options in terms of their potential operational and scientific value. However, this study did not analyse coincident collection opportunities with reference missions. Further details on the orbit selection and propulsion options are provided in Section 5.1.

In the Pathfinder orbit scenario, an SSO with an average altitude of 550 km was chosen since a non-SSO orbit does not provide the solar illumination consistency required for accurate forest fuel flammability assessment.

Orbital analysis performed during the study found a 170 days revisit time without spacecraft cross-track slewing (nadir imaging) for any point on the Earth. However, if a cross-track slew of 20 degrees is allowed, then the instrument line-of-sight (LOS) could image Canberra's National Arboretum 16 times per 90-day interval. Fewer access opportunities are available as the allowable spacecraft slew angle is decreased. Access can be increased if the field of view of the instrument around the LOS is increased. Section 5.1 provides details of this analysis.

In addition, the ConOps provides for regular interruption of normal operations to perform instrument calibration. Calibration may come in several forms: vicarious, lunar, or onboard calibration. However, onboard calibration capability is not considered for the Pathfinder mission. Further details on the calibration approach can be found in Section 0.

For the constellation mission, the implementation of the OzFuel ground segment would ideally leverage the expertise and capabilities of the Australian National Ground Segment Technical Team (ANGSTT) for a constellation mission. For the Pathfinder mission, direct arrangements with industry ground station providers are appropriate, where L0 data is transferred from the ground station to the science team located at ANU for higher-level processing.

Following best practices, communications between the space and ground segments should implement authentication and authorisation. Encryption may be considered, and a security risk assessment should be undertaken. These activities are outside the scope of a Pre-phase A study and should be considered during the detailed system development.

Further details on the data processing pipeline, including how external stakeholders would be able to interface with the different subsystems, are also yet to be developed.

4.5.2 Mission operations centre

The study did not fully consider the details of the design of an OzFuel mission operations centre (MOC).

In general, the required MOC infrastructure that services either the Pathfinder or a Constellation would include the following:

- Software tools to propagate and visualise spacecraft orbits and ground station passes.
- Software tools to encode telecommands and decode telemetry into human-readable data safely and automatically.
- Software tools for visualisation and trending of spacecraft telemetry.
- Software tools to optimise spacecraft tasking and automatically output the required telecommands.
- Software tools that allow telecommands to be generated, reviewed, approved, and sent to a ground station for transmission to the spacecraft.
- A filterable cloud-based database of communications between the ground stations and the spacecraft. This database would include all uplinked commands and all responses received, including housekeeping telemetry, configuration data, payload data, and spacecraft log files.
- Methods to set warning limits for telemetry fields for operators to be immediately notified of non-nominal spacecraft health.
- Methods to export and share telemetry and payload data in accessible formats.

4.5.3 Sustainability of operations concept

To reduce the accumulation of space debris, Earth-orbiting missions must adhere to disposal policies defined at a national level or by the customer. Section 4.6 of NASA Standard 8719.14, *Process for Limiting Orbital Debris*[13] states that a spacecraft with a perigee altitude below 2000 km shall be disposed of by leaving it in an orbit in which natural forces would lead to atmospheric re-entry within 25 years after the completion of the mission or manoeuvre the spacecraft into a controlled deorbit trajectory as soon as practical after completion of the mission.

Typically, spacecraft in orbits above 600 km altitude cannot naturally re-enter the atmosphere within 25 years and require an end-of-mission manoeuvre for controlled re-entry or to reduce the orbital altitude to enable re-entry within 25 years.

A deorbiting manoeuvre is only possible if the end-of-mission is planned; that is, the mission objectives have been completed to the extent possible, and a decision is made to proceed to the disposal phase of the spacecraft while the bus is still functional. If a critical platform component fails during the mission, the spacecraft may not be able to re-enter within the required 25 years. For a planned deorbit manoeuvre, NASA recommends that the probability of post-mission disposal should be no less than 0.9, with a goal of 0.99 or better[14]. Therefore, any Pathfinder mission should target an orbit of 500-600 km altitude.

All planned, confirmed, and cancelled manoeuvres for orbit insertion and station keeping would be reported to the 18th Space Defence Squadron (18 SDS) as per 18 SDS's Spaceflight Safety Handbook for Satellite Operators[15]. Additionally, regular ephemeris data from the onboard GPS receiver would be supplied to 18 SDS to improve the accuracy of the catalogue entries and conjunction assessments for the OzFuel spacecraft.

---

[13] NASA, 2019, Process for Limiting Orbital Debris, NASA-STD-8719.14B, https://standards.nasa.gov/standard/osma/nasa-std-871914.

[14] US Government, 2019, Orbital Debris Mitigation Standard Practices, https://orbitaldebris.jsc.nasa.gov/library/usg_orbital_debris_mitigation_standard_practices_november_2019.pdf

[15] 18th Space Control Squadron, 2020, Spaceflight Safety Handbook for Satellite Operators, Version 1.5, https://www.space-track.org/documents/Spaceflight_Safety_Handbook_for_Operators.pdf.

4.6 Mission requirements

The OzFuel Pathfinder mission requirements that the study participants developed are listed in Table 2.

Table 2 OzFuel preliminary mission requirements

ID	Title	Description	Rationale	Comment
OZF-M-1	Capability building	The mission shall contribute to the development of an Australian space industry capability.		
OZF-M-2	Budget	The mission cost, including satellite(s), launch and operations, shall be less than AUD 6M.		To be confirmed.
OZF-M-3	Lifetime	The mission lifetime shall be at least 24 months in orbit.		Only science mission life. Excludes launch and early operations (LEOP) and commissioning.
OZF-M-4	Schedule	The development of the mission from contract award to FRR shall be no more than 36 months.		Timeline to be confirmed. FRR: Flight readiness review.
OZF-M-5	Satellite	The mission shall utilise one spacecraft in orbit.		Pathfinder mission.
OZF-M-6	Orbit	SSO; 600 km altitude (nominal) 12:00-14:00 LTAN (to be derived from science requirements)	Considering that forest fuel flammability traits such as Fuel Moisture Content (FMC) change seasonally and throughout the day, it is desirable to acquire data in the early hours of the afternoon (12h00-14h00) when vegetation is more stressed and can be more easily ignited. [RD-2]	A constant illumination angle is critical during image acquisition between successive observations. A launch and commissioning in winter are desired to ensure operations can begin in spring (the start of typical bush fire season).
OZF-M-7	Operational attitude	The satellite shall provide an operational mode to support observations with a continuously fixed attitude with respect to the orbital reference frame.		
OZF-M-8	Platform	The payload shall be compatible with the Skykraft Block 2 Platform, which is based on the current Skykraft platform.		This study did not consider other Australian platform providers as likely candidates for the mission.

ID	Title	Description	Rationale	Comment
OZF-M-9	Slewing	The satellite shall provide an operational mode to support observations after slewing in the cross-track direction up to 20 degrees.		
OZF-M-10	Focal plane array	The mission shall utilize data from an optical imaging payload based on the SAPHIRA eAPD SWIR detector array, Rosella FEE, and Thales cryocooler.		Heritage: EMU, SPIRIT. FEE: Front-end electronics.
OZF-M-11	Multi-spectral bands	The mission shall observe in four SWIR spectral bands.		
OZFM-12	Image acquisition	The mission shall support the collection of snap-frame and rolling shutter (TDI) imaging operations.		Time delay integration (TDI) is an imaging technique.
OZF-M-13	Ground Station Location	The mission shall only consider ground stations located in Australia.	Sovereignty and capability building.	
OZF-M-14	Data Processing	Raw (L0) image data shall be downlinked from the spacecraft to a ground station(s) in Australia and disseminated to the user's location for processing into higher-level image data products.		L1 generation on board is a secondary requirement or goal.
OZF-M-15	Time-tagged image data	The system shall provide a time tag for all acquired image data.		Synchronise payload and ADCS with platform clock.
OZF-M-16	Attitude and orbit data	The system shall be capable of providing attitude and orbit data.		Enables processing of L0 to higher-level image data products.
OZF-M-17	On-ground instrument calibration	The mission shall provide the capability to utilise a suitable facility for instrument on-ground geometric, radiometric, and spectral calibration.		
OZF-M-18	On-orbit instrument calibration	The mission shall provide the capability and processes to perform periodic instrument on-orbit geometric, radiometric, and spectral calibration.		

ID	Title	Description	Rationale	Comment
OZF-M-19	Image data products	**Level 0 products:** Raw data at full space/time resolution with all supplementary information (i.e. metadata such as orbital data, time conversion or sensor state) to be used for subsequent processing. Level 0 data will be time-tagged for ease of use. **Level 1A products:** Level 0 products with the necessary geometric and radiometric corrections applied. Level 1A products are annotated with satellite position and consist of Top of Atmosphere (TOA) radiance ($W \times m^{-2} \times sr^{-1} \times \mu m^{-1}$) data. **Level 1B products:** Level 1B products are orthorectified, re-sampled to a specific grid and geo-located. **Level 2 product:** Product 1B with atmospheric corrections. Level 2A product consists of surface reflectance (unitless) data. **Level 3 product: Maps of Leaf-level traits that influence flammability (**Fuel Moisture Content, volatile organic compounds and structural carbohydrates).	See [RD-2]	Re-sampling can be performed using several methods, including bi-cubic interpolation or nearest neighbour.
OZF-M-20	Revisit time	The mission shall provide the capability to image a region of interest (ROI) at least once every 21 days (8 days for the operational mission).	Eucalypt structural carbohydrates and volatile organic compounds don't change from day to day. Users need weekly updated Fuel Moisture Content (FMC) data products.	An ideal repeat coverage should be higher than that for Landsat sensors (i.e. every 16 days) and similar to that of the combined Sentinel 2A and 2B satellites (i.e. every three to five days). [RD-2]
OZF-M-21	Image strip length	The mission shall support imaging of up to 700 km strip in snap frame mode.		

ID	Title	Description	Rationale	Comment
		The mission shall support imaging of a strip of up to 50 km in rolling shutter (TDI) mode.		
OZF-M-22	Design Sizing	The mission shall be designed to support a 512 x 512 pixel 24 μm eAPD array with no significant added development cost.	Upgrading to a larger sensor will increase the swath width, thus reducing the revisit time.	Goal. Allows for larger detectors in future generation FPAs.
OZF-M-23	Contamination Control	The mission shall provide adequate means to control particulate and molecular contamination of the instrument.		

4.7 Space Segment requirements

The OzFuel space segment (i.e. platform and payload) requirements developed by the study participants are listed in Table 3. Based on their current platform, the Skykraft 'Block 2' platform was considered the baseline to host the OzFuel sensor and support mission operations.

Table 3 OzFuel space segment preliminary requirements

<table>
<tr><th>ID</th><th>Title</th><th>Unit</th><th>OzFuel Pathfinder</th><th>OzFuel Full Operational capability</th><th>Note/Comments</th></tr>
<tr><td>OZF-S-1</td><td>GSD</td><td>m</td><td>50-60</td><td>20-30</td><td>For OzFuel Pathfinder, studies suggest that some algorithms for species discrimination and phenology have a similar prediction accuracy when pixel sizes ranging between 20m and 60m are used. [RD-2]</td></tr>
<tr><td>OZF-S-2</td><td>Swath (derived)</td><td>km</td><td>16</td><td>25.6</td><td>Based on the baseline Saphira detector: 320 x 256 pixels, 24 µm. The operational mission would host a 512 x 512 pixels detector.
Expected swath width as a function of GSD [RD-2]
<table>
<tr><th>GSD (m)</th><th>No. of Pixels Nominal</th><th>Swath width (m)</th></tr>
<tr><td>20</td><td>320</td><td>6400</td></tr>
<tr><td>30</td><td>320</td><td>9600</td></tr>
<tr><td>40</td><td>320</td><td>12800</td></tr>
<tr><td>50</td><td>320</td><td>16000</td></tr>
<tr><td>60</td><td>320</td><td>19200</td></tr>
</table></td></tr>
<tr><td>OZF-S-3</td><td>Region of Interest (ROI)</td><td>km</td><td>500 x 500</td><td>TBD</td><td>The ROI could be centred on the ACT and include parts of Western Sydney and designated calibration/test sites (e.g. sites in Western Australia)</td></tr>
</table>

<table>
<tr><th>ID</th><th>Title</th><th>Unit</th><th>OzFuel Pathfinder</th><th>OzFuel Full Operational capability</th><th>Note/Comments</th></tr>
<tr><td>OZF-S-4</td><td>Revisit time</td><td>day</td><td>21</td><td>6-8</td><td>For the Pathfinder, a revisit time at the Arboretum test site of 21 days is acceptable. A single spacecraft with 20 deg cross-track slewing can provide this capability.</td></tr>
<tr><td>OZF-S-5</td><td>Spectral band definition</td><td>-</td><td><table>
<tr><th>Band</th><th>Band centre (nm)</th><th>Band width (nm)</th></tr>
<tr><td>1</td><td>1205</td><td>10</td></tr>
<tr><td>2</td><td>1660</td><td>10</td></tr>
<tr><td>3</td><td>2100</td><td>10</td></tr>
<tr><td>4</td><td>2260</td><td>10</td></tr>
</table></td><td>Increased number of bands</td><td>See RD-2 for spectral band characteristics of OzFuel.</td></tr>
<tr><td>OZF-S-6</td><td>Spectral SNR</td><td>-</td><td>Greater than or equal to 100:1</td><td>Greater than or equal to 100:1</td><td>In all bands. [RD-2]</td></tr>
<tr><td>OZF-S-7</td><td>Off nadir image angle</td><td>deg</td><td>+/- 20</td><td>+/- 20</td><td>Improve target acquisition frequency. Effects of the bidirectional reflectance distribution function could impact radiometric accuracy and resolution.</td></tr>
<tr><td>OZF-S-8</td><td>Absolute pointing error</td><td>deg</td><td>< 0.75</td><td>< 0.75</td><td>Key platform requirement. It is driven by the requirement to have the target within the image.</td></tr>
<tr><td>OZF-S-9</td><td>Absolute pointing knowledge</td><td>arcsec</td><td>9 arcsec</td><td>9 arcsec</td><td>Key platform requirement. It is driven by geo-referencing requirements (OZF-S-11). This requirement may need a fine attitude determination system to be met, such as a star tracker.</td></tr>
</table>

ID	Title	Unit	OzFuel Pathfinder	OzFuel Full Operational capability	Note/Comments
OZF-S-10	Line-of-sight Pointing jitter	arcsec RMS	< 1.8	< 0.75	Key platform requirement. MTF degradation due to 0.1-pixel smear during the integration time (7 ms). A trade of smear contributions to imaging performance and platform stability must be performed.
OZF-S-11	Image Geo-referencing accuracy	GSD	0.5	0.5	
OZF-S-12	Absolute Radiometric Accuracy (on orbit)	%	5	5	To be confirmed. To be derived from the radiometric sensitivity (OZF-S-14).
OZF-S-13	Relative Radiometric Accuracy (on orbit)	%	TBD	TBD	Band ratioing is not used to compute science parameters.
OZF-S-14	Radiometric sensitivity (NEdL)	$W/m^2/sr/\mu m$	TBD	TBD	
OZF-S-15	Radiometric stability	% / unit time	TBD	TBD	
OZF-S-16	Bit rate	bits	12	12	16 bits would not bring significant benefits due to achievable SNRs.

ID	Title	Unit	OzFuel Pathfinder	OzFuel Full Operational capability	Note/Comments
OZF-S-17	Frame rate mode (snap frame)	fps	3	3	Baseline operative mode, allowing for a TBD amount of filter overlap.
OZF-S-18	Frame TDI mode (min)	fps	140	140 (orbit dependent)	Supports nominal TDI mode where $T_{int} = T_{dwell}$ of 1 pixel on the ground.
OZF-S-19	On-board data storage (total)	GB	128	256	For Pathfinder: 64 GB operational and 64 GB redundant.
OZF-S-20	Data compression	--	TBD compression ratio	TBD compression ratio	Lossless data compression with TBD technique. 2.5:1 is the CCSDS-123.0-B general hyperspectral data compression ratio lower bound.
OZF-S-21	Calibration frequency (on-orbit)	days	30	30	The baseline is vicarious calibration without an onboard calibrator. More frequent during LEOP and monthly during science operations.
OZF-S-22	Detector operating temperature	K	100	100	Baseline design using Thales cryocooler; Leonardo specifies 100K as within the operating temperature range.
OZF-S-23	Spectral filter operating temperature	C	< -70 (for detector wavelength cut-off of 3.5 µm)	< -70 (for detector wavelength cut-off of 3.5 µm)	The SAPHIRA MCT detector can go to 3.5 um. For detector wavelength cut-off of 2.5 um, the operating temperature can be relaxed to 0 C. Consider filter physical integrity at cold temperatures.
OZF-S-24	"Cool" stop/baffle operating temperature	C	TBD	TBD	To be determined in future analyses.

ID	Title	Unit	OzFuel Pathfinder	OzFuel Full Operational capability	Note/Comments
OZF-S-25	Payload Dimensions	mm	360 x 240 x 135	TBD	Based on Skykraft's current platform. The payload shall be compatible with Skykraft Block 2 bus.
OZF-S-26	Spacecraft Mass	kg	36	TBD	Estimate based on Skykraft Block 2, Blue Canyon's FlexCore ADCS. Includes a 1.5 kg margin. Details are in *Appendix D: OzFuel preliminary mass budget*.
OZF-S-27	Payload Power	W	35	TBD	Average power in imaging mode (70 s events). Details in *Appendix E: OzFuel preliminary power budget*. Estimate based on Skykraft Block 2, Blue Canyon's FlexCore ADCS.
OZF-S-28	Payload downlink data rate	Mbps	2	TBD	Supports snap frame imaging over Pathfinder ROI area with opportunistic TDI mode imaging events.
OZF-S-29	Ground stations	-	1	TBD	Preferably Australia-based.

4.8 Observational requirements

Observational requirements for the Pathfinder mission are based on the science objectives described in [RD-2]. A notional Pathfinder concept of operations defined a ROI covering the National Arboretum in Canberra, ACT. This ROI would be designated as a test/calibration site and serve as the primary imaging region for the Pathfinder mission.

Observational requirements for a constellation will be addressed in the future.

4.9 Timeline

The implementation timeline will be based on the need to operate in parallel with other Australian missions, such as SCR and AquaWatch. A program development schedule of 36 months (OZF-M-4; Schedule) has been proposed.

To achieve this goal, detailed design work on the OzFuel mission should be started as soon as funding is secured. The schedule is driven by the following critical elements that were identified during the mission risk assessment:

- Development and qualification of the Rosella electronics and the FPA architecture.
- Qualification of the TheMIS cryocooler.
- Modifications to the Skykraft platform (development of the Block 2 platform) to meet the OzFuel mission requirements.

5 Systems engineering analyses

This section reports the ANCDF team's analyses in this study's scope. At this stage of the OzFuel mission, several key trade-offs have been identified. These include:

- Orbit selection (linked to reference mission selection)
- Instrument design options
- Spacecraft mass range/form factor
- Propulsion
- Number of star trackers
- Payload data downlink RF band and spacecraft antenna concept
- Ground station locations
- MOC staffing
- Model philosophy/Design, Development and Verification Plan
- Off-nadir imaging in ConOps – Attitude determination and control system (ADCS) design driver

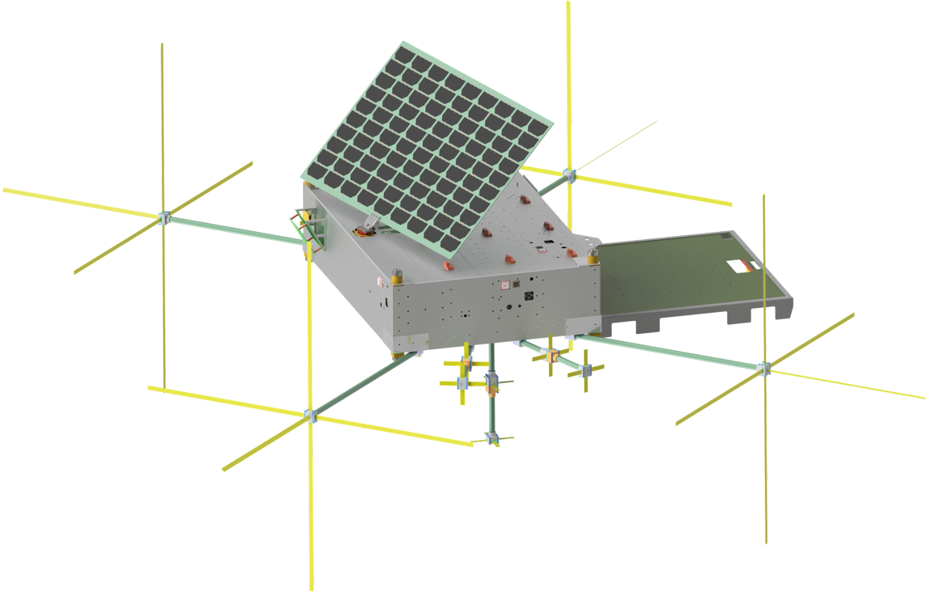
5.1 Spacecraft conceptual design

The spacecraft conceptual design is based on the Skykraft Block 2 satellite platform, with Skykraft's Air Traffic Management payloads removed and modifications made to accommodate the OzFuel payload.

The Skykraft Block 2 satellite platform was selected because it is a locally developed platform (allowing for easier engineering integration of the payload), has a suitable payload volume, has a relatively mature design, and is low-cost. It weighs approximately 30kg and measures 900mm x 600mm x 200mm (when stowed).

The Block 2 platform with Air Traffic Management payloads is shown in Figure 2.

Figure 2 Skykraft Block 2 satellite platform, configured with the Air Traffic Management Payloads



The spacecraft subsystems include the ADCS elements, mission computer, power management, communications, and thermal control subsystems.

5.2 Orbit selection and revisit time

A preliminary orbit analysis was conducted as part of the study. This section provides the supporting analyses to facilitate orbit selection and inform the design of a propulsion subsystem if needed.

Orbit options that minimize the revisit time for a single spacecraft over a designated calibration site at the National Arboretum in Canberra were considered. This approach aligns with the Pathfinder mission objective to maximize the number of acquisitions at the calibration site to advance the achievement of the mission science goals.

5.2.1 Orbit selection and contact times

The primary orbit selection criterion for the Pathfinder is to optimise the revisit time over Canberra's National Arboretum calibration site. The observation time needs to be consistent each day, where the ideal local time is between 12h00-14h00 as vegetation is most stressed and more prone to ignition in the early afternoon. A GSD of less than 100m is required, but an ideal GSD is between 50 and 60 m. Since the SAPHIRA detector (320 x 256 24 µm pixels) has only 320 pixels in the cross-track direction, the required GSD limits the swath width to 16 km (320 x 50 m GSD).

The orbital analysis assumes an altitude of 550 km and a GSD of 50 m, producing a 16 km swath width. The relevant orbit parameters are listed in Table 4.

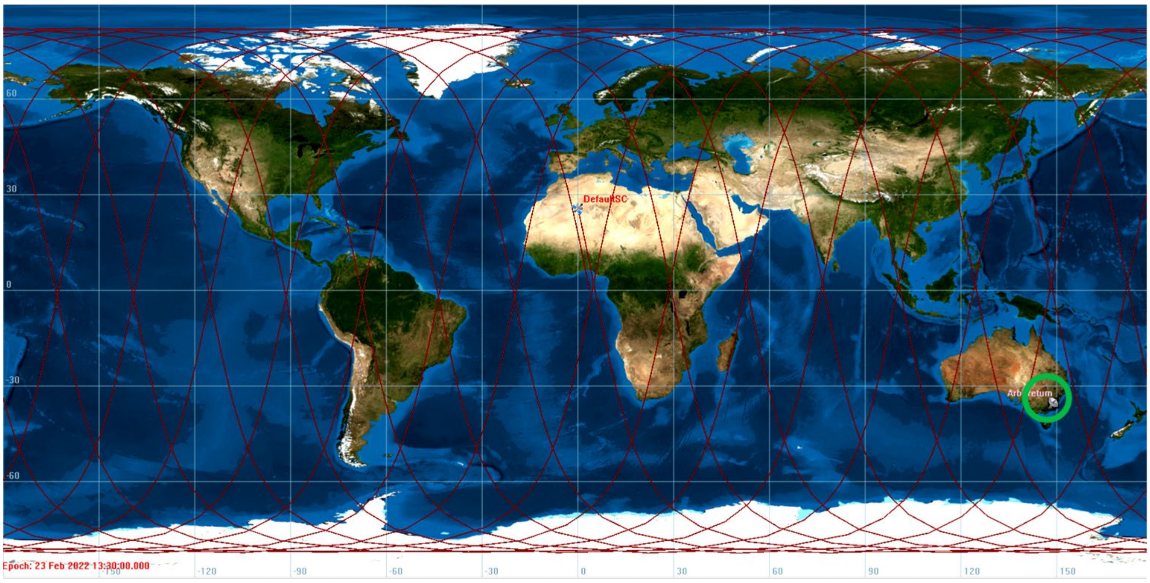
Table 4 Parameters for notional OzFuel Pathfinder orbit

Orbit Parameters: 550 km altitude; local cross time 13:30	
Semi-major axis	6926.43 km
Eccentricity	0.001
Inclination	97.586 deg
Right angle of ascending node	358.3 deg
Argument of perigee	0 deg
True anomaly	0 deg

Such an orbit and sensor would require 170 days to cover the Earth with no gaps. The limiting factor is the relatively small sensor swath width. However, a constellation of satellites would reduce the repeat cycle. For example, a 28-day repeat cycle could be achieved with 6 spacecraft, and a 7-day repeat cycle could be achieved with 24 spacecraft. This part of the analysis assumed that the OzFuel sensor was positioned in a nadir-viewing position.

A graphical representation of the daily orbit tracks is presented in Figure 3, where Canberra's Arboretum calibration site is highlighted.

Figure 3 Daily orbital track of the OzFuel Pathfinder



The repeat cycle for a single spacecraft can be reduced if imaging is allowed in off-nadir conditions. The repeat cycle is further shortened by increasing spacecraft slew angle limits. Several orbit options in the 500-600 km altitude range allow for 10 to 16 acquisitions of the Arboretum site every 90 days, assuming a 10 to 20-degree slew. The number of ROI contacts in a 90-day interval as a function of slew angle is presented in Table 5.

Table 5 Number of ROI contacts vs spacecraft slew angle for a 90-day observation window

Spacecraft slew angle (deg)	Number of ROI contacts
20	**16**
15	12
10	10
5	3
0	0

During the study, it was decided that maximising the collection opportunities over the Arboretum calibration site with spacecraft slewing is acceptable.

However, the derived surface reflectance of an ROI is usually directional and depends on the incident solar and receiving detector angles. Imaging at off-nadir angles of 10 degrees or more introduces radiometric uncertainty due to changes in the perceived target reflectance. Additional analysis or experimentation should be performed to determine the maximum off-nadir view angle that maintains science requirements.

For further details, a slide deck summarising the orbital analysis results performed during the study is included in *Appendix B: Orbit analysis summary slide deck*.

5.2.2 Propulsion considerations

Two operational needs may drive the need for on-board propulsion for the mission:

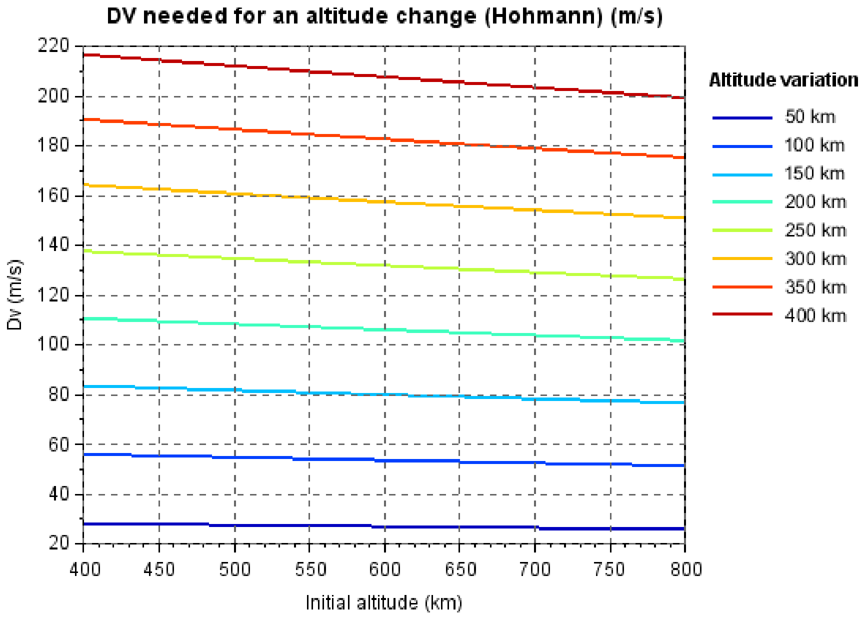
- Compliance with space debris mitigation standards, notably the need to vacate the LEO region within 25 years after the end of the nominal mission, as explained in Section 4.5.3.
- Station acquisition or station-keeping needs in a constellation scenario.

The 25-year goal can be achieved by leveraging the atmospheric drag of the spacecraft. This is typically achievable for micro- or nanosatellites at orbital altitudes below 600 km. At higher altitudes, the atmospheric density does not provide sufficient drag to achieve the desired re-entry timeframe.

Station acquisition may be necessary if the OzFuel spacecraft is launched as a secondary payload and the primary payload on that launcher is targeting a different orbit than the selected one. It may be required to manoeuvre the spacecraft to the final orbit on its own accord.

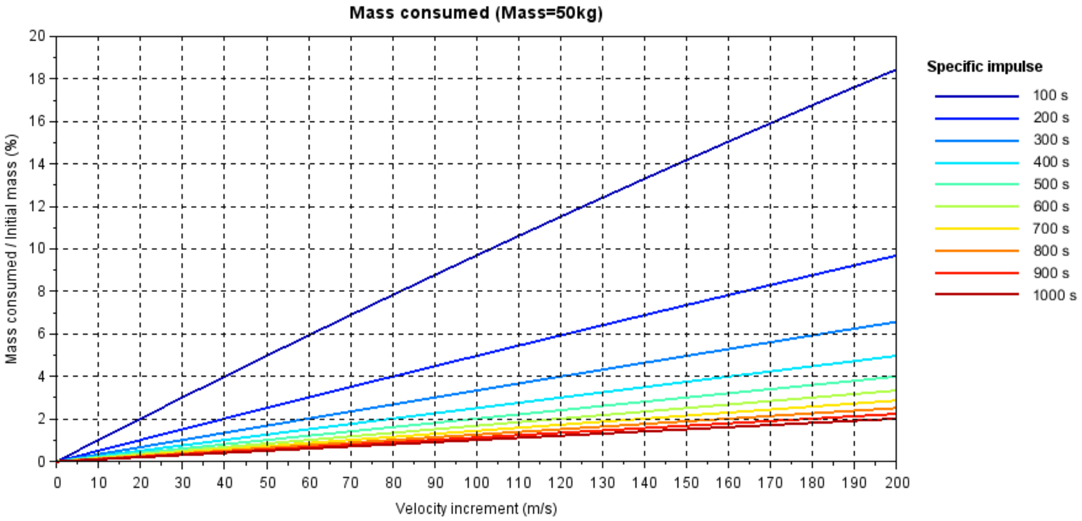
The total impulse required for deorbiting or station acquisition is expected to be much larger than any station-keeping needs. This is because the orbit may need to be changed significantly, whereas only minor adjustments are required in a station-keeping scenario. Figure 4 maps the required delta-V for a Hohmann transfer between an initial orbit of a given altitude and a given altitude change. It should be noted that utilising Hohmann manoeuvres in the LEO region yields an error of less than 5%, even compared to realistic continuous low-thrust manoeuvres. This example shows that moving a satellite from a 700km orbit to a 500km passive re-entry orbit would require slightly over 100m/s delta-V.

Figure 4 Circular-to-circular orbit manoeuvre delta-V requirement as a function of initial orbit altitude and change in altitude



The required total delta-V, in combination with the selected propulsion technology, would determine the mass fraction of the propellant to the satellite's dry mass ratio. This relationship is plotted exemplarily for a notional 50kg spacecraft in Figure 5. The range of specific impulse (Isp) values included in the graph represents the range as achievable by cold gas (<100s) over chemical (150s – 350s) to electrical (>1000s) propulsion subsystems. Thus, for a required delta-v of 100m/s (200 km altitude change), a cold gas system would require 5 kg of propellant (10% of total mass), while an electrical system would need 0.5kg of propellant (1% of total mass). But note that electrical propulsion systems require more mass for solar arrays, batteries, and power management systems to support the electric thruster than for cold-gas systems.

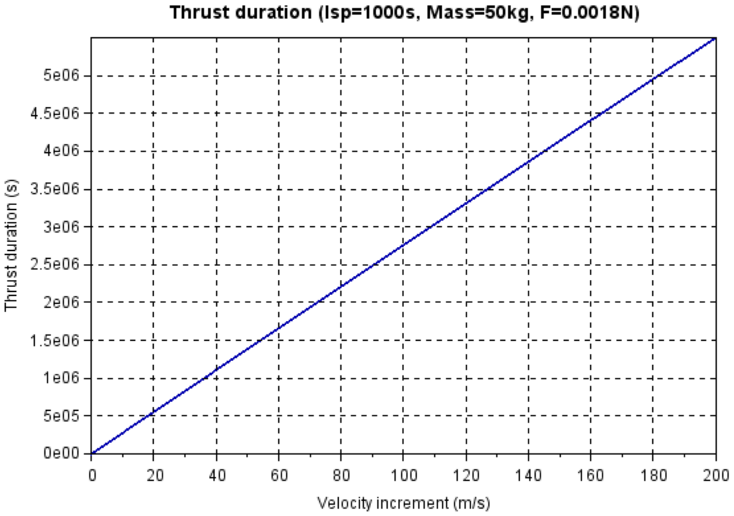
Figure 5 Propellant mass fraction depending on delta-V and specific impulse of the propulsion subsystem



While fuel efficiency increases for higher Isp propulsion subsystems, thrust decreases. Typical thrust levels for Hall-effect thrusters (Isp ~1000 s) are 1 to 30 mN. This relatively low thrust requires a substantial thrusting period to achieve a particular orbit change.

Continuing the above example, achieving a delta-V of 100m/s with 1.8 mN of thrust requires 3E6 s or 35 days of continuous thrusting, as plotted in Figure 6. This calculation does not consider the incidence of insufficient electrical power during eclipses, which typically extends the thrusting period by approximately 50%.

Figure 6: Thrust duration as a function of delta-V for a 1.8mN thruster on a 50kg satellite



The selected propulsion technology must balance all presented conflicting effects to meet the mission goals best.

5.3 Payload design

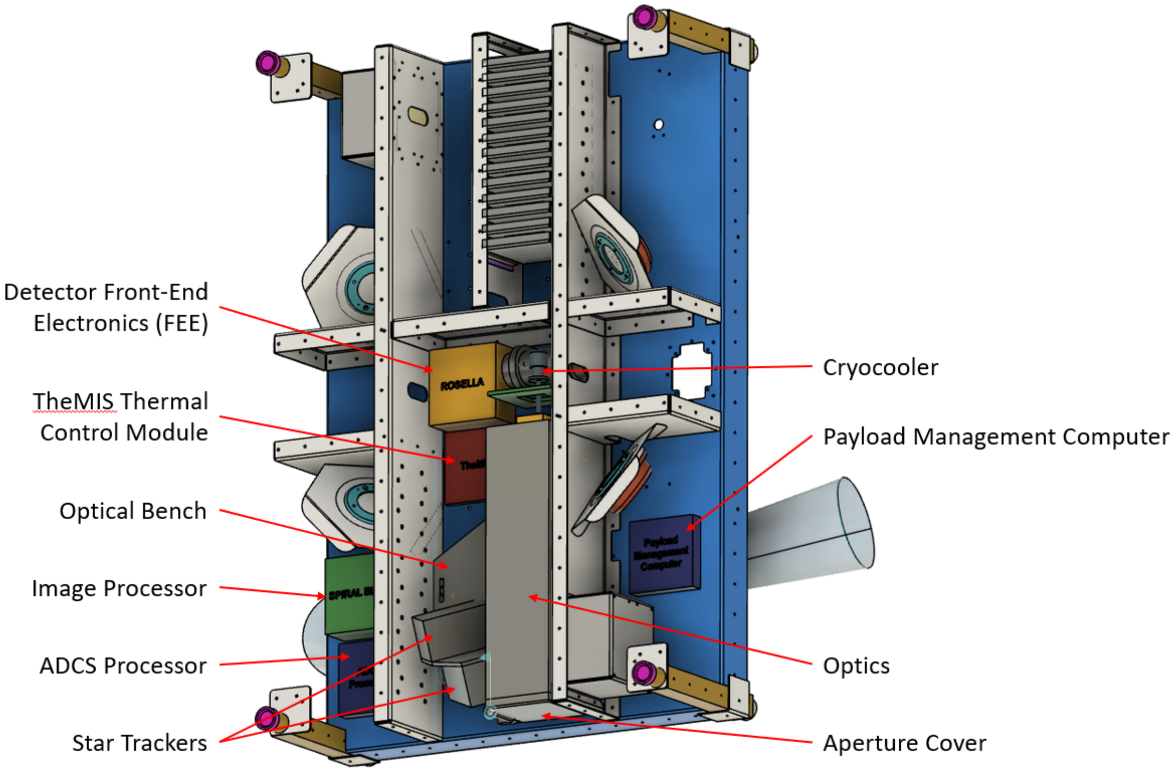
5.3.1 Payload concept overview

The Block 2 payload bay volume is approximately 360 x 240 x 135 mm; slightly larger than a 6U). The OzFuel payload architecture includes the following subsystems:

1) The OzFuel instrument based on an:
   - ANU custom optical system (based on the CHICO instrument)
   - ANU developed FPA and front-end electronics (FEE) assembly:
     - The Leonardo SAPHIRA APD 320 x 256 / 24 µm pixel IR sensor
     - The ANU Rosella high speed/low noise FEE
2) The TheMIS active thermal management system developed by the Melbourne Space Lab (MSL), University of Melbourne. It is based on the Thales LSF9987 cryocooler[16] and is capable of active cooling to 80K at the cold tip.
3) A payload management module (PMM) that provides power and data interfaces to the platform and instrument.
4) An image data processor developed by Spiral Blue.

A conceptual configuration for the payload and the platform's major subsystems is shown in Figure 7.

Figure 7 OzFuel payload and major subsystems



The grey rectangular volume in the centre of the figure represents the allotted volume for the OzFuel optical system. It was initially sized based on the CHICO instrument, which is larger than ANU's preliminary OzFuel optical design volume. The principal instrument elements include the Rosella Front-End Electronics (FEE), Spiral Blue's Image Processor, the PMM, the TheMIS controller, the Thales cryocooler, and the ADCS processor.

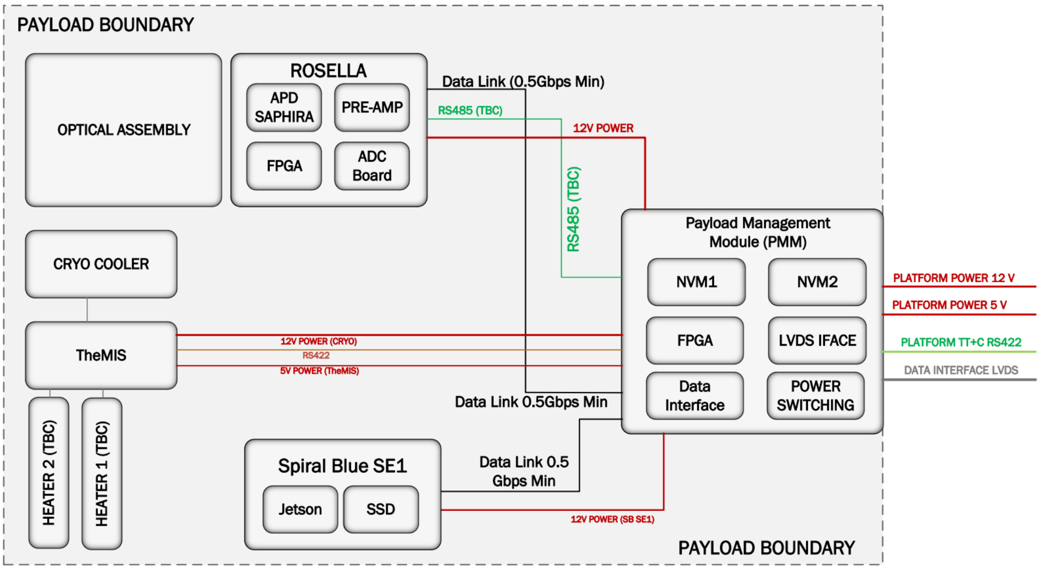
---

[16] Therakam, C., et al., "The SpIRIT Thermal Management System (TheMIS)", 51st Intl., Conf. on Environmental Sciences, 10-14 July 2022, ICES 2022-163, 2022.

Since the spacecraft chassis is not thermally stable, the instrument would be mounted on an isolated optical bench which would then be mounted to the spacecraft via three isostatic mounts. This would prevent spacecraft thermal distortions from affecting the instrument's optics. Star trackers are also mounted to the optical bench to provide precise pointing knowledge of the instrument. A deployable aperture cover is also used on the optics to prevent contamination before operation in orbit.

A functional block diagram of the Payload elements and electrical interfaces is shown in Figure 8.

Figure 8 OzFuel Payload preliminary block diagram



The PMM receives power from the spacecraft platform and has power and data interfaces to the instrument, TheMIS and the Spiral Blue processor. It incorporates an FPGA (Field Programmable Gate Array) device that interfaces with the instrument for telemetry, tracking and command (TT&C) and retrieving image data. A high-speed 0.5 Gbps data link has been included for the imaging scenarios discussed during the study.

5.3.2 Payload optical assembly design

A preliminary optical design for the OzFuel payload was developed during the study to meet the mission requirements. A summary slide deck is included in *Appendix C: OzFuel optical system design and analysis*. The first-order requirements for the optical assembly design are listed in Table 6.

Table 6 Optical payload requirements

Optical payload requirements
50 m GSD at 550 km orbit
Bands: 1205 nm, 1660 nm, 2100 nm, 2260 nm (10 nm bandwidth)
Assumed a volume restricted to an 85 X 85 X 310 mm cuboid (3U).
Accommodate less than 7.5 ms exposure times and required radiometry (not considered here)

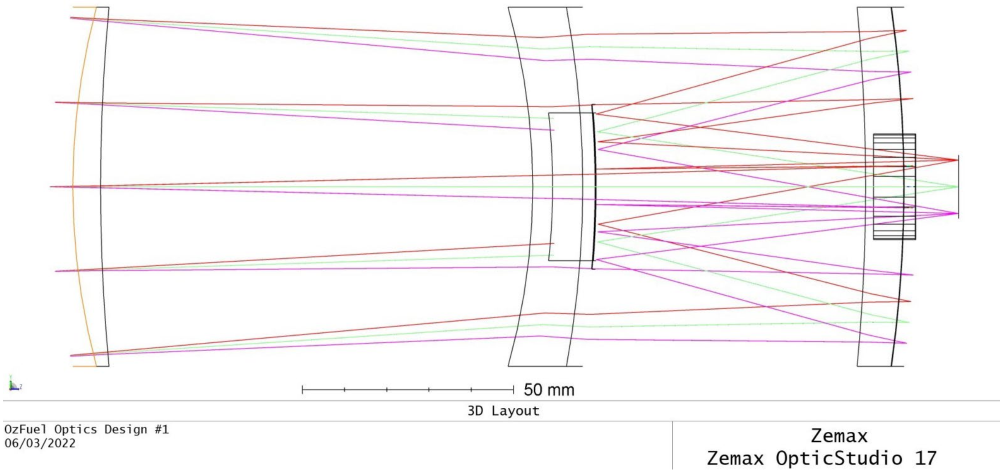
A preliminary design was derived from the above properties for volume, spectral performance and image quality using the SAPHIRA detector with 320 x 256 / 24 µm pixels. The derived parameters are listed in Table 7.

Table 7 Optical payload first order performance parameters

Optical system parameters for the SAPHIRA Detector	
Array Format	320x256
Pixel Pitch	24 µm
Focal length needed for 50 m GSD at 550 km	264 mm
Image circle diameter	10 mm
f/# (assuming 85 mm aperture)	2.2

A more in-depth analysis was performed in the weeks following the study, which led to a report by ANU.[17] Two designs were investigated, and both met the OzFuel imaging requirements. The baseline design (design #1) was refined and deemed the most favourable regarding manufacturability. Figure 9 presents a layout of this design, which is based on a Schmidt-Cassegrain optical construction.

Figure 9 Baseline optical payload configuration



An IR-blocking filter was discussed as part of the baseline design. The blocking filter's minimal operational temperature is -70 C. Therefore, a thermal stop ('cool stop') must also be included in the design to keep the filter within the operational temperature range. Table 8 list the relevant parameters for this design.

Table 8 Baseline optical system parameters

Design parameters for Design #1	
Aperture	85 mm (square)
Length	215 mm
Complexity	3 elements, 1 asphere, no exotic materials
SNR	200 (worst-case)
Spectral filter location	Cemented to the focal plane

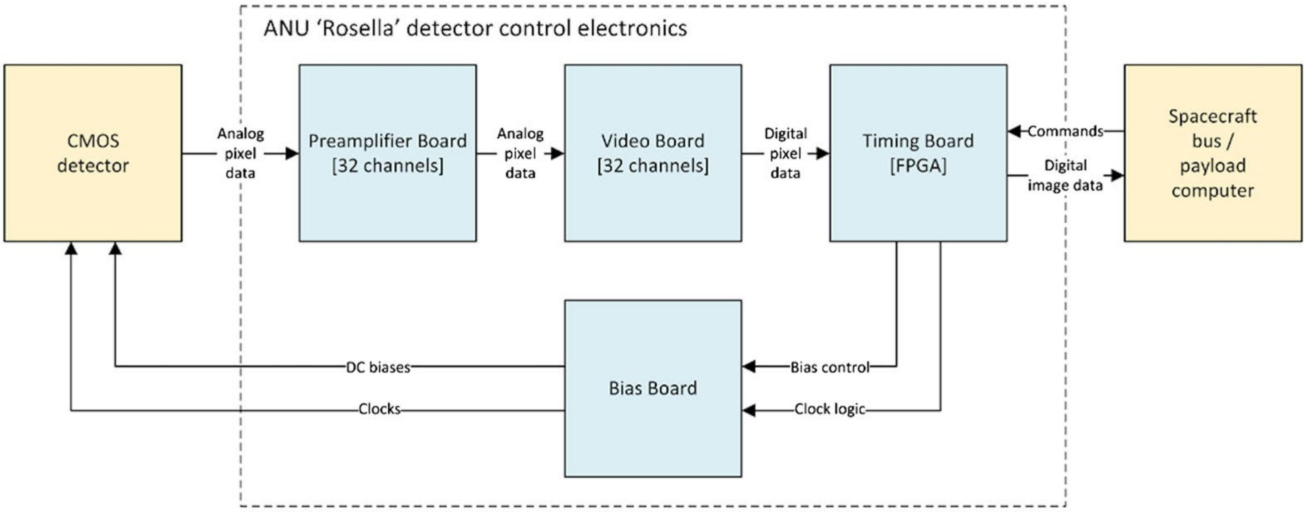
---

[17] Vaughn, I., OzFuel: Telescope Design Trade Study Preliminary design concepts, OZFUEL-OZFUEL-TRS-0004, Version 1

5.3.3 FPA and FEE design and performance

The design of the FPA is based on the Leonardo SAPHIRA detector and the Rosella FEE, currently at TRL 4-5. Rosella is a modular and compact detector controller for space applications under development by ANU. This high-performance Field-Programmable Gate Array (FPGA) based readout system can be configured to interface with a wide range of visible and infrared CMOS detectors, including Leonardo SAPHIRA eAPD and Teledyne HxRG family of shortwave infrared arrays. The system is highly configurable to deliver high-performance, be that frame rate, noise level or bespoke windowed readout. The Rosella electronics architecture includes a preamplifier board, bias board, video board, and an FPGA-based timing board (Figure 10). The preamplifier board reduces the effect of electrical noise on the detector output signals by matching the detector output impedance. The output signals are then converted to cross-correlated differential signals to remove external interference before the signal is digitized. The bias board is responsible for generating stable and accurate DC voltages for the SAPHIRA detector and variable gain bias.

Figure 10 Rosella electronics architecture overview (credit: ANU)

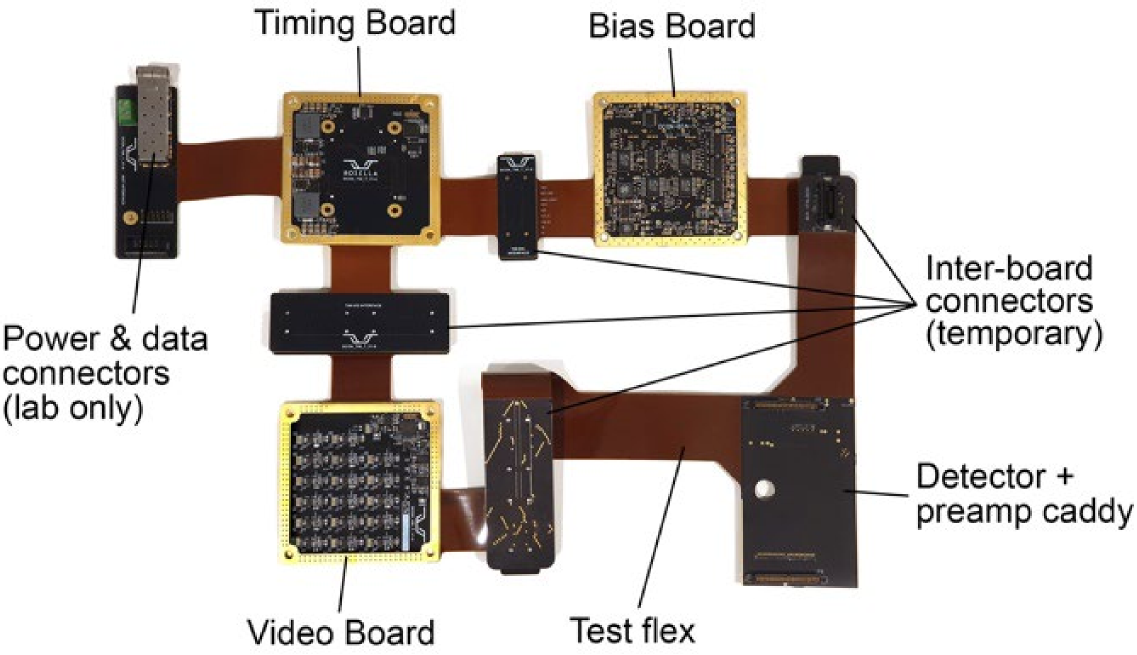


The video board currently under active development has 32 parallel Analogue to Digital Converter (ADC) channels for digitizing the pixel stream from the detector targeted to support the Leonardo SAPHIRA eAPD array. By design, Rosella is configurable for larger and smaller array operations. Rosella delivers a low readout noise system, which is critical for SAPHIRA-like detectors. The timing board is responsible for managing the entire system, including clock pattern generation, bias configurations, ADC triggering, image processing, and communication with an external payload computer via a standard protocol. Rosella provides a simple and low-level interface to a satellite mission control computer for high-level tasking, as well as direct output to GPU systems to support onboard AI analysis and real-time value-added data analysis for data compression.

The Rosella concept was initially designed for the Emu astronomy space mission. Rosella can support frame rates up to 1 kHz with a high-ground resolution for Earth Observation missions in mind.

Rosella's final version occupies a volume of ~0.5 U, comprising a connector-less printed circuit board (PCB) assembly based on rigid-flex technology. A 'FlatSat' model of Rosella is shown in Figure 11.

Figure 11 Rosella 'FlatSat' engineering model (credit: ANU)



Rigid PCB sections have an outer thermal conduction region that interfaces with an aluminium wall, forming a contiguous and enclosed board stack by folding the flex circuit sections. The enclosure also provides the right tightness for payloads sensitive to infrared emission (thermal "glow"). A mock-up of the PCB and enclosure assembly is shown in Figure 12.

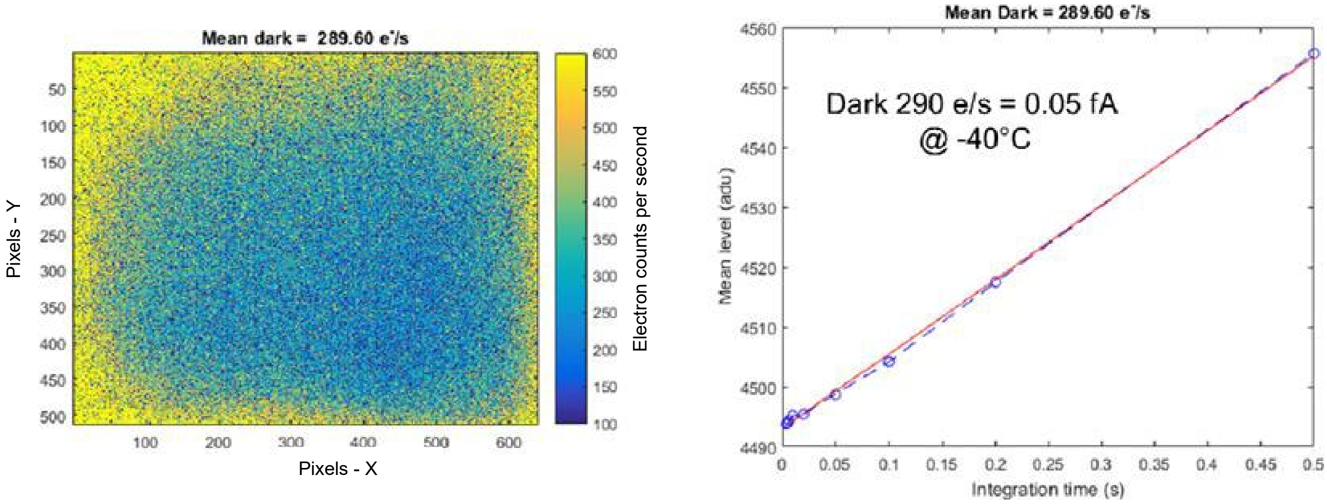
Figure 12 Rosella 0.5 U enclosure mock-up showing interleaved PCBs and aluminium enclosure walls (credit: ANU)

Science data products, particularly bushfire fuel load indices, must have high fidelity and low uncertainties. Therefore, the FPA and FEE must be run at cold temperatures (100 K, OZF-S-22) to provide an adequate signal-to-noise ratio (SNR) of the collected data.

An example of sensor performance is shown in

Figure 13, where the dark current as a function of integration time is shown when the operating temperature of the FPA is -40 C.[18]

Figure 13 Right-hand side: Dark current vs integration time. Left-hand side: Dark current map per pixel.



The TheMIS thermal management system cools the FPA and FEE to the required temperature. It is capable of active cooling to 80K at the cold tip, with a heat load capacity of 650 mW at 23 C.

ANU presented a preliminary SNR calculation and indicated that shot noise-dominated performance could be achieved in all bands. In this case, the primary noise source resides in the very nature of light and cannot be overcome. A summary of the achieved SNRs with the proposed design is presented in Table 9.

Table 9 Preliminary SNR summary

Band (nm)	**SNR**
1205	654
1660	451
2100	165
2260	155

---

[18] Data courtesy of ANU Institute for Space.

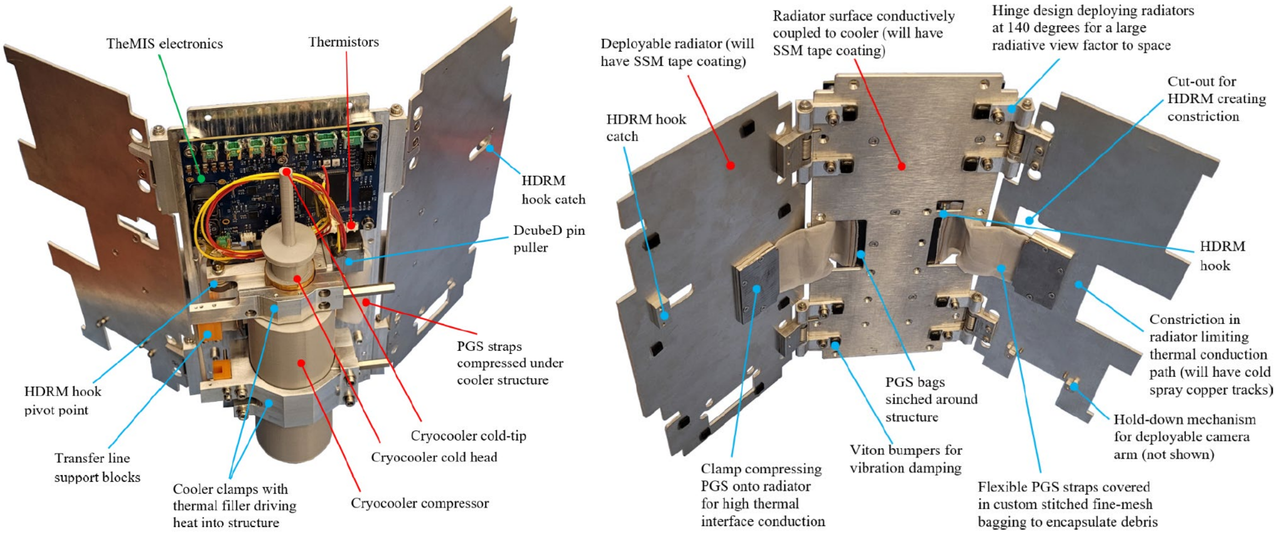
5.3.4 TheMIS payload thermal management module

<u>This paragraph (in italics) and the figures below are an extract from the following paper</u>: The SpIRIT Thermal Management Integrated System (TheMIS) (2022). C. Therakam, S. Barraclough, S. Catsamas, M. Ortiz del Castillo, J. McRobbie, R. Mearns, M. Ohkawa, A. Chapman and M. Trenti. 51st International Conference on Environmental Systems ICES-2022-163, 10-14 July 2022, St. Paul, Minnesota.

> *The Thermal Management Integrated System (TheMIS) is a key element of the payload of the Australia-Italy Space Industry Responsive Intelligent Thermal (SpIRIT) mission. SpIRIT is a collaborative effort led by the University of Melbourne between the Australian space industry, academia and the Italian Space Agency to promote cooperation in space exploration and further the maturity of the Australian space sector. Part of a broader University of Melbourne R&D focus on advanced remote sensing from nanosatellites, TheMIS has the ability to both actively cool and control the temperature of sensitive instruments, opening up the potential for more capable payloads on small spacecraft systems. This capability is achieved using a Commercial off-the-shelf (COTS) Stirling Cycle Cryocooler, in-house developed control electronics, pyrolytic graphite sheet thermal straps and deployable radiators, including a hold down and release mechanism. To date, this degree of thermal control has not been used on small spacecraft systems, however, with advances in cooling technology and spacecraft components, the ability to increase the performance of sensors through active cooling is opening up. To give the system a development focus and demonstrate its capability in a real-world example, TheMIS will manage the thermal environment of SpIRIT's HERMES payload, an X-ray instrument that will be provided by the Italian Space Agency. However, beyond this mission, TheMIS has the potential to support multiple other applications such as low-noise infrared imaging and increased resilience of electronics to space weather. TheMIS aims to provide the space industry with a technology that is seen as a key product to improve sensor performance in a range of different areas. The SpIRIT project has designed and developed a 6U CubeSat mission that will provide the opportunity for TheMIS to gain flight heritage.*

TheMIS is based on the Thales LSF9987 cryocooler. It is used to keep the OzFuel sensor cooled down to the required temperatures, as outlined by requirements OZF-S-22, OZF-S-23 and OZF-S-24 in Section 4.7. Figure 14 shows a visual of the TheMIS system.

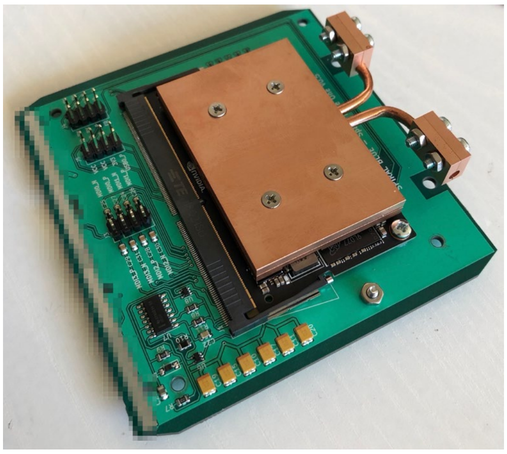
Figure 14 Front (left) and back (right) view of TheMIS (credit: MSL)



5.3.5 Onboard image processor

Spiral Blue’s Space Edge (SE) Computer is based on Nvidia computing modules. Spiral Blue designs and manufactures a motherboard and cooling system to operate these modules in space, interfaced with satellites. The motherboard provides additional storage, power conditioning, transceivers, and other interfacing hardware. Cooling assemblies and radiation shields are also part of the payload package. A visual of the Space Edge computer is presented in Figure 15.

Figure 15 Spiral Blue's Space Edge computer (credit: Spiral Blue)



Spiral Blue has developed middleware software to manage the payload in orbit. This software enables telemetry capture, logging of application executions (1st and 3rd party), uploading software updates and new applications, downlinking outputs, and general software maintenance.

Specifications of the current Space Edge Computer are provided in Table 10.

Table 10 Space Edge Computer specifications

Specification	Space Edge 1 (SE-1)
Chip	NVIDIA Jetson Xavier NX
Processing power	21 TFLOPS (FP16)
	Time to process images will depend on the app/s used
GPU	384 Volta CUDA cores and 48 Tensor cores
CPU	6-core NVIDIA Carmel ARMv8.2 64-bit CPU
Memory	8GB
Storage	> 250GB
Interfacing	Hardware: CubeSat form factor, option to build to other form factors UART, CAN, Ethernet, and USB hardware interfaces are available. Others may be included as required. Communications through UART/CAN/HTTP, Data through HTTP. Requires API provided by satellite operator or Spiral Blue
Size	Smaller than 0.25U (25x96x90mm)
Weight	300g
Power	3W idle, 20W peak, 6W avg
	Minimum run time of 10 minutes
Radiation	Metal shielding, options for composite or polymer shielding. Software redundancy, backups, encoding. Testing is to be completed in 2022.
EMI Interference	Minimal (to be quantified)
Thermal control	Integrated heat pipes must be in contact with an external heat reservoir or radiator to operate continuously
Software	Linux Ubuntu 18.04-based OS, Docker-based containers
Design life	5 years
TRL	Currently at TRL 6. TRL 7 expected in Q4 2022

5.3.6 Payload calibration

Critical for any EO mission, calibration activities begin with pre-launch calibration and continue throughout the mission with regularly scheduled in-flight calibration operations.

The OzFuel mission objectives for calibration would be the same as for other EO missions, where OzFuel would conduct pre-flight SI-traceable and on-orbit calibration using terrestrial pseudo-invariant calibration sites (PICS) or an on-board calibration subsystem.

Tools for characterizing the geometric, radiometric, and spectral performance of OzFuel and generating data correction parameters must be developed to ensure a traceable and rigorous calibration to the SI (metric system) standard.

Pre-flight calibration:

Establishing the baseline OzFuel performance on the ground is critical to mission success. Best practice methods for assessing instrument component and subsystem performance before and during assembly, alignment and instrument testing must be rigorously employed to understand the uncertainties in performance and construct reliable performance error budgets.

The characterization and calibration of the OzFuel instrument would be planned and implemented in conjunction with the instrument development to meet the overall performance requirements. These activities would occur in a well-established facility explicitly designed for space-based optical instrument calibration.

In addition to radiometric and spectral calibration, an instrument-level image quality assessment would be performed. Critical parameters such as the instrument impulse response function (IRF) would be measured using appropriate targets and delivery systems. In addition to the OzFuel image quality, the pointing of the instrument with respect to the spacecraft axes would be established to meet geo-referencing requirements.

In-flight calibration:

The goal of in-flight calibration is to correct for short and long-term changes in the instrument response due to the harsh conditions of the space environment. Although there may be excellent repeatability in the IRF measurements in the short term, the response will likely have an overall drift or localised anomalies in a long time series of measurements.

Periodic in-flight calibration corrects the instrument responsivity that accounts for the likely performance degradation of the optical and detector components, which can occur in the space environment.

The absolute radiometric accuracy and sensitivity requirements are still to be determined and will need to be established with respect to the science and image product fidelity requirements.

In-flight calibration could be achieved by using an onboard passive solar calibrator to take 10-100 exposures at an interval to be determined. In-flight instrument calibration is an area needing more detailed analyses to set these radiometric performance and system design requirements.

5.4 Satellite platform assessment

5.4.1 Attitude Determination and Control

The main driving requirement for the ADCS performance is overall geolocation and georeferencing accuracy. For the OzFuel Pathfinder, the requirement is 0.5 pixels or 25 m (0.5 GSD) on the ground (OZF-S-11). An operational altitude of 550 km translates this into an absolute pointing knowledge (APK) of less than 9 arcsec.

If the National Arboretum ROI is assumed to be a 3 km x 3 km wide target, its presence in the FOV leads to an absolute pointing error (APE) of less than 0.73 deg.

Other points were noted, including:

- The pan/tilt relative pointing error must remain below 0.5 deg/s.
- The roll error requirement is less stringent.
- High-frequency platform jitter needs to remain below 1.8 arcsec RMS.
- The primary reaction wheel jitter usually has a lower frequency than is relevant for a 1 ms exposure.
- Ground motion and platform rotation effects are cumulative in the 'tilt' direction.

APE, APK and pointing jitter error requirements were discussed during the study and led to requirements for the OzFuel platform summarised in Table 11.

Table 11 Pointing analysis requirement summary

Performance Metric	Value	Unit	Mission Driver
Off nadir image angle	+/- 20	deg	Revisit time
Absolute pointing error (pointing control accuracy)	< 0.75	deg	Target in the image (within instrument FOV)
Absolute pointing knowledge	9.0	arcsec	Pixel geolocation
LOS Pointing jitter	<1.88	arcsec	Image Smear (image quality degradation)

While Skykraft's current platform cannot meet these pointing requirements, an initial canvassing of currently available off-the-shelf ADCS subsystems showed that the Blue Canyon Flexcore system meets the mission pointing requirements and can be integrated into the Skykraft bus. Blue Canyon's ADCS subsystem is estimated to cost 700k AUD.

Whether Blue Canyon components are required on the Block 2 platform will be determined after an in-orbit demonstration of the Skykraft Block 2 platform. This document assumes that the Skykraft Block 2 platform does not meet the mission's pointing requirements.

5.4.2 Power generation and management

The spacecraft must provide sufficient power generation capability to ensure the power budget remains positive throughout the commissioning and nominal operations of the spacecraft. The power generation should be implemented using triple junction solar cells. Depending on the Skykraft Block 2 platform configuration, the payload power requirements, and the final mechanical configuration of the spacecraft, deployable solar arrays may be required.

The spacecraft shall have sufficient energy storage to support operations through eclipse periods and to supplement power generation sources in high-power operations. Lithium batteries are commonly used, but other chemistries may be more appropriate depending on operational and environmental requirements. The battery shall be capable of supplying the required surge currents (peak and continuous). It shall be appropriately sized so that it is not discharged beyond safe limits during eclipses and high-power operations (a maximum depth-of-discharge of 20-30% for lithium-based chemistries is typically accepted).

A preliminary power budget was developed during the study and is presented in *Appendix E: OzFuel preliminary power budget*. It is built on the assumptions presented in

Table 12.

Table 12 Electrical Power Subsystem design assumptions

Parameter	Assumption	Comment
Number of solar cells	90	Spectrolab UTJ cells.
Platform energy consumption	10 W continuous	Equivalent 16.1 Wh/orbit. Includes flight computer, radio (uplink) and electrical power system. Excludes ADCS.
ADCS energy consumption	17 W continuous	Equivalent to 27.4 Wh/orbit.
Acquisition event	16 x 500 km strip	70 s following Table 13.
Acquisition event energy consumption	16.2 Wh / acquisition	Includes 1 h of cooling (TheMIS) before acquisition. Detailed calculation in Appendix E.
Number of acquisitions events per day	2 / day	Assumed 15 orbits/day.

Based on those assumptions, the following parameters regarding the power state of the platform were computed and grouped in Table 13:

Table 13 OzFuel Energy budget

Parameter	Result (Wh/orbit)	Result (Wh/day)	Comment
Energy generation	85.2	1279	Includes a 50% reduction margin to account for contingencies. 2558 Wh/day with no margin.
Instrument and ADCS energy consumption	29.5	443.2	ADCS in continuous operation. Two acquisitions per day.
Energy consumption for all other subsystems	16.1	241.5	Equivalent to 10 W continuous. Includes flight computer, radio (uplink) and electrical power system.
Energy margin	39.6	594.3	

The system will be power positive if all subsystems other than the instrument and ADCS can be operated with the assumed 10W continuous power.

It is worth noting that extending the acquisition duration from 70 s to 350 s (from 500 km to 2500 km strip length) does not impact the energy budget significantly and would be readily achieved from an energy perspective. Indeed, the instrument and ADCS energy consumption would only go up by about 1.6 Wh/day. However, other considerations, such as data handling and storage, downlinking capacity and thermal loadings, may not allow longer image strips. Further analyses are required to evaluate the maximum imaging strip length precisely.

Based on this preliminary analysis and the payload diagram presented in Figure 8, the spacecraft electrical power subsystem (EPS) will need to supply to the instrument and ADCS the power levels shown in Table 14:

Table 14 Platform to Payload power supply levels

PLATFORM TO SUPPLY PAYLOAD		
Voltage Rails	**Power (W)**	**Peak (W)**
12V	30.2	63.74
5V	10.5	11
24V	12	150

5.4.3 Mass estimation

Based on the conceptual spacecraft configuration, a preliminary mass budget was created. The entire mass budget is presented in *Appendix D: OzFuel preliminary mass budget*.

In summary, an allocated spacecraft mass of 38 kg was calculated and included a system-level margin of 3.5 kg. The platform mass was assumed to be equal to the Skykraft current platform for this computation, as the Block 2 platform's mass is yet to be fully confirmed.

5.4.4 Communications

The study identified the need for two communication links: a Telemetry, Tracking, and Command (TT&C) link and a payload data downlink link.

The TT&C link commands the spacecraft, checks its state of health, and performs any software reconfigurations/updates. These activities typically generate a few megabytes of data per day. As such, the channel can be designed to operate at a low data rate and with a wide-beam antenna, making signal acquisition easier. A channel data rate within 0.01 – 1 Mbit/sec is likely sufficient for this mission by similarity with other comparable missions. Depending on the risk tolerance and expected mission lifetime, a second TT&C link could be included to provide redundancy if the first link fails. An omnidirectional antenna allows communications to be established without requiring spacecraft platform pointing; a design should include this feature where possible. Otherwise, successful communications depend on the correct functioning of the ADCS (for antenna pointing). Standard frequency bands for TT&C include UHF and S-Band, both well-supported by various ground station implementations.

The payload downlink communication link can be a high data-rate communication channel in the S-Band or X-Band frequency range. These frequency ranges allow the use of existing ground station infrastructure, significantly reducing the cost of obtaining data from the spacecraft by leveraging existing infrastructure and partnerships. S-Band and X-Band are commonly available through ground station networks and can be utilised to meet the data budget needs of this mission. Ka-Band is becoming more prevalent and could be utilized if there is a significant change to the data budget.

5.5 Ground segment assessment

5.5.1 Data volume estimation

The OzFuel instrument will generate a potentially large amount of data in each orbit. How much data is generated depends on the image acquisition mode and the number of samples per image which is determined by the GSD, image swath and strip length of any ROI.

Discussions during the study focused on imaging only Australia and led the team to consider the National Arboretum calibration site as having priority for the Pathfinder mission. A preliminary calculation was performed to estimate the generated data volumes as a function of the strip length. The results are shown in Table 15. The baseline parameters of 50 m GSD and 16 km cross-track swath obtained with the SAPHIRA detector were assumed along with a 12-bit analogue-to-digital converter.

Table 15 Preliminary data volume generation

Strip length (km)	Data volume (Bytes/orbit)	Acquisition duration (sec)	Acquisition duration (min)
2500	6.14E+09	354.65	5.91
2000	4.92E+09	283.72	4.73
1500	3.69E+09	212.79	3.55
1000	2.46E+09	141.86	2.36
500	1.23E+09	70.93	1.18
250	6.14E+08	35.46	0.59
100	2.46E+08	14.19	0.24
50	1.23E+08	7.09	0.12
25	6.14E+07	3.55	0.06
5	1.23E+07	0.71	0.01

In most cases, the data downlink rate and volume from a satellite to a ground terminal will be limited by the availability of on-board data storage, limitations in the data channel bandwidth and the duration of the temporal transmission window when the satellite has a line of sight to a ground station.

The OzFuel communications subsystem will need to be sized to accommodate the desired operational mode (size of the imaged area) that will, in turn, drive the produced data volume.

Reducing the amount of transmitted data is a critical mission issue that can be addressed using compression techniques. Image compression removes redundant or non-relevant information, encodes what remains, and reduces the amount of transmitted data. Various compression algorithms[19] [20] [21] can be employed to extract the salient information in an image and its representation by fewer samples than in the original raw image. These include JPEG2000, wavelet, PCA and DCT-based algorithms, to name a few. These algorithms are typically deployed in space-

---

[19] Yu, G., Vladimirova, T., and Sweeting, M., "Image compression systems on board satellites", Acta Astronautica, **64**, 988-1105 (2009)

[20] Dusselaar, R., and Manoranjan, P., "Hyperspectral image compression approaches: opportunities, challenges and future directions:discussion", J. Opt. Soc. Am. A 34, 2170-2180 (2017).

[21] Puri, A., at al., "A comparison of hyperspectral image compression methods", Int. J. Comp. and Elec. Eng., **6** (6) (2014).

qualified ASIC[22], FPGA[23],[24] and GPU[25],[26] hardware for speed rather than in software. The specific compression algorithm and performance depend on the detector's performance; however, it is reasonable to assume a 2:1 compression ratio.

5.5.2 Ground station network

The ground station network is critical to any space mission as it commands the spacecraft and receives its telemetry and status. It also downloads the payload data to the ground. Utilising a single ground station is cheaper but utilising multiple ground stations increases the amount of data that can be downloaded daily from the spacecraft.

The following ground station (GS) sites were considered viable candidates for the OzFuel mission, as they are either located in Australia or a partner country.

1) Alice Springs, NT, Australia (-23.758970, 133.881859)
2) Hobart, TAS, Australia (-43.057600, 147.317783)
3) Cape Ferguson, QLD, Australia (-19.269191, 147.054298)
4) Learmonth, WA, Australia (-22.234866, 114.094383)
5) Christmas Island, Australia (-10.4890419, 105.6443757)
6) Sioux Falls, SD, USA (43.735932, -96.622455)
7) Hartebeeshoek, South Africa (-25.887705, 27.706159)
8) Svalbard, Norway (78.2305661, 15.3793643)

Table 16: Ground station network options and associated daily contact times

Station combination								**Total visibility (min/day)**	**Comment**
1	2	3	4	5	6	7	8		
🟩								35	Australian GS only
	🟩							45	Australian GS only
🟩	🟩							52	Australian GS only
🟩	🟩			🟩				82	Australian GS only
🟩	🟩				🟩			102	
🟩	🟩				🟩	🟩		131	
🟩		🟩	🟩					63	Australian GS only
🟩		🟩	🟩		🟩			108	
🟩		🟩	🟩		🟩	🟩		141	
🟩	🟩	🟩	🟩					76	Australian GS only
🟩					🟩			75	
🟩					🟩		🟩	229	

---

[22] Brower, B., et al., “Advanced space-qualified downlink image compression ASIC for commercial sensing applications”, Proc. SPIE **4115**, 311-319 (2000).

[23] Caba, J., “FPGA-based on-board hyperspectral imaging compression: benchmarking performance and energy efficient against GPU implementations”, Remote Sens., **12** 3741 (2020).

[24] Li, L., et al., “Efficient implementation of the CCSDS 122.0-B-1 compression standard on a space qualified field programmable gate array” in Journal of Applied Remote Sensing 7.1 (2013).

[25] Keymeulen, D., et al., “GPU lossless hyperspectral data compression system for space applications”, 2012 IEEE Aerospace Conference, 2012, pp. 1-9, doi: 10.1109/AERO.2012.6187255.

[26] Diaz, M., “Real-time hyperspectral image compression onto embedded GPUs”, in IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, vol. 12, no. 8, pp. 2792-2809, Aug. 2019, doi: 10.1109/JSTARS.2019.2917088.

There is limited additional contact time gained by using multiple Australian stations; the benefit of a second Australian station is the redundant capability in case of a ground station failure, not an increase in contact time. Pairing an Australian station with an international station significantly increases contact time. For example, the Sioux Falls (USA) station adds about 40 minutes per day.

For the Pathfinder mission, a single Australian ground station (e.g. Alice Springs) is sufficient to downlink the amount of data generated from imaging the National Arboretum calibration site and surrounding regions, given the relatively contained data volume that is generated (estimated to be 2 GB per day, assuming an average of two acquisitions per day over Australia given the chosen orbit).

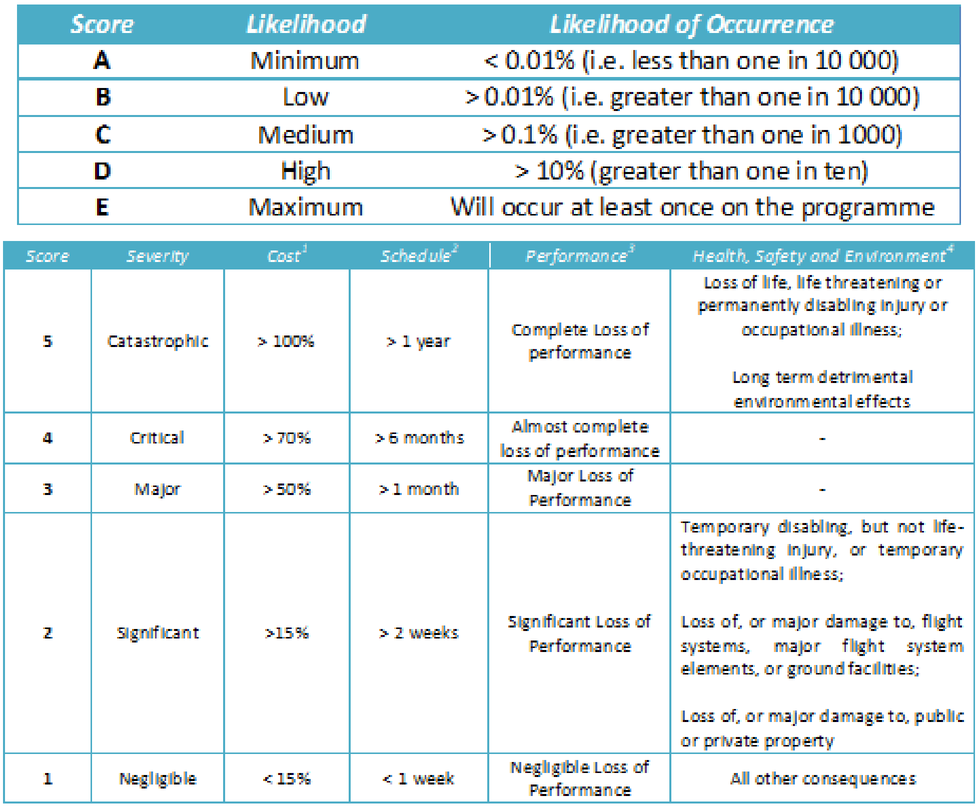
5.5.3 Processing pipeline and data distribution

An on-ground processing pipeline was not analysed in sufficient detail for the OzFuel Pathfinder mission to develop a concept or cost estimate. Its architecture depends on the detailed ConOps and whether the data is integrated into a broader EO data dissemination system.

5.6 Risk assessment

A risk assessment and mitigation exercise was conducted with the participants as part of the study, and a preliminary risk register was prepared. All risks were classified on a likelihood and severity of impact scale, as described in Figure 16.

Figure 16 Risk likelihood and severity index



Score	Likelihood	Likelihood of Occurrence
A	Minimum	< 0.01% (i.e. less than one in 10 000)
B	Low	> 0.01% (i.e. greater than one in 10 000)
C	Medium	> 0.1% (i.e. greater than one in 1000)
D	High	> 10% (greater than one in ten)
E	Maximum	Will occur at least once on the programme

Score	Severity	Cost[1]	Schedule[2]	Performance[3]	Health, Safety and Environment[4]
5	Catastrophic	> 100%	> 1 year	Complete Loss of performance	Loss of life, life threatening or permanently disabling injury or occupational illness; Long term detrimental environmental effects
4	Critical	> 70%	> 6 months	Almost complete loss of performance	-
3	Major	> 50%	> 1 month	Major Loss of Performance	-
2	Significant	>15%	> 2 weeks	Significant Loss of Performance	Temporary disabling, but not life-threatening injury, or temporary occupational illness; Loss of, or major damage to, flight systems, major flight system elements, or ground facilities; Loss of, or major damage to, public or private property
1	Negligible	< 15%	< 1 week	Negligible Loss of Performance	All other consequences

The risks were then classified into high, medium, and low-impact categories as per the schema shown in Table 17.

Table 17: Risk magnitude classification scheme

Risk magnitude		**Severity of impact**				
		Negligible	Significant	Major	Critical	Catastrophic
Likelihood	Maximum	Low	Medium	High	High	High
	High	Low	Medium	Medium	High	High
	Medium	Low	Low	Medium	High	High
	Low	Low	Low	Medium	Medium	High
	Minimum	Low	Low	Low	Medium	High

Notable high risks are a cryocooler or TheMIS system failure; or hardware and software failures associated with the Rosella FEE. A failure of either component would render the instrument sensor unusable. Other risks were associated with long lead item procurements and schedule delays.

The risk matrix is presented in *Appendix F: OzFuel Risk register.*

6 Mission element development

This chapter provides a high-level overview of all mission elements and compares differences in procurement options to provide a rough order of magnitude (ROM) cost for each. These estimates are based on UNSW Canberra actuals for previous missions in a comparable size class as OzFuel (UNSW's M2 mission). However, refinements are required and should be provided by potential bidders for the mission. This information is then used to establish a bottom-up ROM cost estimate for an OzFuel mission. The description of each element is kept brief here.

6.1 Payload

6.1.1 Description

Procurement of payload design and manufacture will leverage knowledge gained through the related missions of AquaWatch and SCR.

The payload requires an optical assembly, an FPA detector, and front-end electronics (FEE). The optical assembly can be developed separately once performance specifications are set and an FPA detector is selected. The same holds for the FEE. Optical and electronic testing services will be required during the integration of these components.

Post assembly, on-ground radiometric calibration of the OzFuel payload would take place in a facility that provides SI traceable sources and known radiance. The programme proposes to procure calibration services from an Australian facility such as NSTF.

6.1.2 Procurement approach aspects

The optical assembly could potentially be sourced from an Australian company or overseas. The FPA detector is likely to be sourced from established vendors such as Teledyne or Leonardo, as no capability currently exists within Australia. The mechanical assembly can be procured in Australia, and the FEE is being developed at ANU (Rosella).

6.1.3 Element cost estimate

The costs associated with the procurement of the payload will be of the same order as the related payloads of the other programs mentioned above, in the order of 1 M AUD (excluding labour). See Section 7 for more details.

6.2 Spacecraft bus

6.2.1 Description

The spacecraft bus houses all the necessary subsystems needed to accommodate and support the payload for the mission's launch and in-orbit operational phases.

The spacecraft bus is a significant portion of the spacecraft and typically consists of the following components:

- Structure, including launch vehicle interface
- Electrical subsystem: batteries, solar arrays, and Electrical Power Supply (EPS)
- Communication subsystems: radios and antennae
- On-Board Computers (OBCs)
- Attitude Determination and Control Subsystem (ADCS): reaction control wheels, magnetorquers, magnetometers, Coarse Sun Sensors (CSS), Earth Horizon Sensors (EHS), GPS, and star trackers (sometimes integrated with optical payloads)
- Thermal control subsystem
- Propulsion subsystem: thruster, propellant storage devices/tanks, and power management system (for electrical propulsion systems)

For this mission, it was estimated that a microsat-sized spacecraft – weighing approximately 30 to 40 kg – would be most appropriate given the expected payload weight and dimensions.

6.2.2 Procurement approach aspects

The programme proposes procuring the Skykraft Block 2 platform due to its suitable payload capability, low cost, relatively mature development, and Skykraft being local to ANU, allowing for easier engineering integration of the payload.

Table 18 lists several platform providers and is included for completeness based on comments during the study that the report should summarise this information.

Table 18 Overview of suitable micro-satellite platforms

Supplier	**Country**	**Microsat Bus**	**Comments**
Skykraft	Australia	Block 2	Will be modified to accommodate the OzFuel payload. Includes launch with other Skykraft spacecraft due to Skykraft's unique dispenser.
Inovor	Australia	Apogee	
Ball Aerospace & Technology Group	USA	BCP-100	Datasheet[27]
Berlin Space Technology	Germany	LEOS-50	Datasheet[28]
Momentus	USA	Vigoride	Datasheet[29]
Raytheon (previously Blue Canyon Technologies Inc.)	USA	X-Sat	Datasheet[30]
RocketLab USA	USA	Photon	Datasheet[31] Includes launch[32]
Satellogic	Argentina		
SSTL	UK	SSTL-Micro	Datasheet[33]
York Space Systems	USA	S-CLASS	Datasheet[34]

Note that all identified off-the-shelf microsat systems for EO missions are from overseas suppliers. Therefore, these platforms or components could be subject to export control, resulting in potentially longer lead times and program delays.

Australian entities Inovor, Skykraft, UNSW Canberra Space and potentially Sitael, have been identified as having demonstrated skills and experience for developing a custom satellite bus that could accommodate the OzFuel payload (by having flown or are being scheduled to fly imminently).

6.2.3 Implementation options

Integrating the payload into the satellite platform would likely be a combined effort between ANU payload engineers and Skykraft engineers, as would the conduct of qualification-level testing.

However, due to Skykraft's unique satellite stacking and deployment technique, Skykraft would be responsible for acceptance-level environmental testing, launch vehicle integration, and early operations. Satellite operations could be a combined effort between Skykraft and ANU.

---

[27] http://www.ball.com/aerospace/Aerospace/media/Aerospace/Downloads/D3072_BCP100-ds_1_14.pdf?ext=.pdf

[28] https://www.berlin-space-tech.com/wp-content/uploads/2020/07/PFR-PR28_LEOS-50__V1.00_.pdf

[29] https://momentus.docsend.com/view/xmuxgesufvqfqh8p

[30] https://www.bluecanyontech.com/spacecraft

[31] https://www.rocketlabusa.com/satellites/

[32] https://www.nasaspaceflight.com/2020/09/rocket-lab-debuts-photon/

[33] https://www.sstl.co.uk/getmedia/78c3ae88-0f17-40a1-9448-8c3c7e9f6944/SSTL-MICRO.pdf

[34] https://www.yorkspacesystems.com/s-class/

6.2.4 Element cost estimate

Skykraft has indicated that the cost of one of their spacecraft would be $4 M AUD.

The spacecraft would be launched along with other Skykraft spacecraft in Skykraft's unique dispenser. This price would include the modifications to the platform, the integration of the payload into the spacecraft, acceptance testing, launch, and operations of the platform and payload (excluding detailed payload operations).

6.3 Flight software elements

Flight software elements weren't explicitly addressed during the study. A spacecraft's flight software comprises the core platform and payload software. The platform software is closely integrated with the underlying electronics and hardware of the spacecraft. The payload software interfaces the payload to the platform onboard computer (for payload TT&C) and the payload radio (for the downlinking of payload data). The payload software may also control the operation of the sensor and any required data read-out and processing. Reliable software is critical to mission success and can jeopardise a mission if severe errors are not addressed or mitigated.

Software development is an ongoing process that spans the life of the mission. Best practices should be adopted so that software scope, complexity and changes can be safely managed throughout the life of the current mission and beyond. Example best practice frameworks include the comprehensive NASA NPR7150.2 (NASA Software Engineering Requirements Standard) framework, which covers software management, planning and life cycle support. However, other standards that may inform a designer's best practice and lifecycle development process include:

- ISO 14950 - Space systems Unmanned Spacecraft Operability (Part of ISO 49.140 - Space Systems and Operations Standards)
- ISO 25010 – Systems and Software Quality Requirements and Evaluation
- NASA-HDBK-2203 - NASA Software Engineering and Assurance (Software implementation guidance for NASA NPR7150.2 and NASA-STD-8739.8)
- NASA-STD-8739.8 - NASA Software Assurance and Software (Guidance on software assurance, safety assessment and Independent Verification and Validation for NASA NPR7150.2)
- NASA-GB-8719.13 - NASA Software Safety Guidebook (Lifecycle guidance on software safety and engineering practices to support NASA-HDBK-2203 and NASA NPR7150.2)

A reliable spacecraft provider would use best practices when developing a fully qualified flight software package.

6.3.1 Platform software

The platform software is often (but not always) provided by the spacecraft bus provider. The software's capabilities depend on the contract agreed upon. The platform software is required to enable the operations of the spacecraft. Some common software elements include:

- Power/thermal management systems
- Fault detection, isolation, and recovery
- Control of any mechanisms or actuators (such as deployable solar panels, antennae, or thrusters)
- Spacecraft TT&C

6.3.2 Payload software

The payload software interfaces the payload sensor to the spacecraft bus and the payload radio. The ability to load a new software package whilst the spacecraft is in-orbit is highly desirable, as it allows defect correction and feature additions to take place post-launch. It is recommended that all relevant subsystems can be reprogrammed in orbit.

6.3.3 Common procurement options

Numerous options for the scope and deliverables of the software package exist. Standard options are listed in the table below.

Table 19: Software package overview and relative cost

Software Package	Notes	Cost
None	The spacecraft bus includes no software. The integrator is expected to write/provide the required software. The bus provider may assist by offering relevant technical information.	Nil
Drivers	The spacecraft bus comes with software drivers for each individual component in the bus. For example, a driver may be provided for the EPS and another driver for the ADCS. These drivers are components and do not form a complete system.	$
Drivers and framework	This likely includes an operating system or similar framework. The framework is designed to integrate the drivers into a cohesive application. The integrator may need to tailor the software to their TT&C requirements or make appropriate adjustments to the ground-based systems.	$$
Whole mission application	Drivers, framework, and any specific NRE required for the mission. This includes integrating the payload software with the platform's OBC and any integration required between the payload OBC and the payload radio.	$$$$

6.4 Assembly, integration, and system-level testing

6.4.1 Description

Integration and system-level testing begin after the individual subsystems and payloads are assembled and tested at a component level. Spacecraft integration activities involve the preparation, assembly, and initial integration tests of subsystems and payloads into the spacecraft structure (bus) and connecting electrical harnesses and heat straps to complete the final spacecraft.

All spacecraft integration procedures require a degree of contamination control since spacecraft are sensitive to particulates, oils and greases, metal filings, and other foreign matter, as the vacuum and weightlessness of space may cause these to coat and degrade optics, cause electrical shorts, and add to debris in orbit. This requires spacecraft to be integrated in special cleanrooms equipped with appropriate air filtration, electro-static discharge (ESD) flooring and workbenches, cleaning equipment such as ultrasonic cleaners, and necessary clothing to prevent people from directly contaminating the spacecraft. In addition, cleanrooms must be stocked with all necessary tools and equipment for assembling, handling, calibrating, and sometimes testing components of the spacecraft.

The system-level testing phase is where the integrated spacecraft with fully developed flight software is rigorously tested to ensure that the spacecraft functions as intended as a complete system. System-level testing is also where the operators get to know the spacecraft intimately and discover operational issues before it is too late to fix them. It is critical that this testing mimics on-orbit operations as closely as possible, which means using the operations software to command the integrated spacecraft over-the-air (no cables) with the spacecraft running the flight software that it would be launched with. This 'test as you fly' approach uncovers bugs and idiosyncrasies that cannot be identified in earlier component-level testing. It is best practice to heavily involve the spacecraft operations team in the planning and execution of system-level testing

6.4.2 Procurement approach aspects

The spacecraft bus integrator would typically perform procurement of integration and system-level testing services, but a third party could be engaged to support these activities.

6.4.3 Implementation options

For spacecraft integration, the system integrator would procure all required subsystems and payloads and run assembly, integration, and system-level test activities. Alternatively, the bus and payload could be contracted, with integration performed by either the vendor or a third party performing the testing.

6.4.4 Element cost estimate

Payload assembly, integration and testing costs are provided in Section 6.7 and are based on UNSW Canberra heritage for the M2 programme. This cost assumes requirements for payload AIT in a cleanroom facility with appropriate staffing.

Spacecraft integration and system-level testing are included in Skykraft's platform cost (see Section 6.2.4).

6.5 Environmental testing and launch

6.5.1 Description

Environmental testing forms part of an overarching effort to provide total mission assurance, i.e., establish the highest level of confidence that the fully integrated system (spacecraft bus and payload) would operate correctly in orbit resulting in a successful mission.

The environmental test program is intended to demonstrate that the as-built system would perform correctly when subjected to a range of environmental conditions (launch and on-orbit operations) more severe than expected during the mission to verify positive design margins. The environmental stress screening activities identify workmanship defects that could jeopardise the mission's success.

Environmental testing is typically conducted in two phases: qualification and acceptance test phases. Qualification tests are conducted on a flight representative engineering model (EM) spacecraft before the final build of the spacecraft to qualify the spacecraft design. Qualification test levels and durations are greater than that used in acceptance level tests to maximise the probability that the final built spacecraft will meet the acceptance tests. Acceptance testing is conducted on the as-built flight hardware just before launch to ensure the spacecraft is acceptable for launch. (It should be noted that environmental testing can be conducted in a single test campaign, known as proto-flight testing. This testing approach does away with the qualification testing stage and applies greater test rigour (qualification levels at acceptance durations) to the as-built flight hardware just before launch. This approach is considered riskier, as it does not allow faults to be rectified and re-tested before launch; it only deems the spacecraft to be flight-worthy or not).

A preliminary design, development, and verification plan (DDVP) was discussed during the study. It was decided during the study that formal system qualification tests would be conducted on a flight representative engineering model (EM) spacecraft. A flight model (FM) spacecraft would be exposed to reduced acceptance level test requirements for flight that are determined by the launch service provider (LSP) specifications.

Detailed environmental qualification requirements depend on the specific mission requirements, the LSP, and the launch vehicle (LV) selected to deliver the system to orbit. The LSP would stipulate the environmental qualification test requirements that must be satisfied so the space system can be accepted for launch into orbit. Therefore, it is critical to baseline an LSP and LV at the outset of the project and engage with the LSP throughout the entire test program to avoid undesired schedule delays and cost excursions later in the project. The latter further minimises the risk of over-testing, thus reducing the risk of unnecessary hardware failure.

The testing requirements and a detailed description of the test schedule should be included in the system verification specification and plan developed at the outset of the project. Environmental qualification testing is typically conducted at a high level of integration on a flight-representative system (or as close to it as possible). Any deviation from the flight-like configuration requires justification and approval from LSP.

In addition, relevant qualification and verification activities may be conducted at several other stages and lower levels of integration along the Assembly, Integration and Testing (AIT) process to provide confidence in the system's operation and compliance with the system requirements as outlined in Section 4.7.

The relevant environmental tests that should be conducted are listed below:

1. Structural model shock test (test results used to correlate spacecraft structural model)
2. Structural test model vibration test (test results used to correlate spacecraft structural model)
3. Engineering model thermal cycling (atmospheric pressure environment)
4. Engineering Model qualification level shock test (**required by LSP**)
5. Engineering Model qualification level vibration test (**required by LSP**)
6. Engineering Model EMC test
7. Engineering Model thermal balance (Vacuum) testing (test results used to correlate spacecraft thermal model)
8. Flight Model Thermal Cycling (vacuum) and Vacuum bakeout (**required by LSP**)
9. Flight Model acceptance level vibration test (**required by LSP**)

6.5.2 Procurement approach aspects

Environmental qualification testing is a critical part of the project workflow and requires suitable facilities and appropriately trained personnel to ensure a successful environmental qualification test campaign. The National Space Test Facility (NSTF) at the Australian National University (ANU) at Mt Stromlo in Canberra can provide the full range of testing services required for environmental qualification of the OzFuel mission except for shock testing. Shock testing can be performed by alternative test houses such as VIPAC in Melbourne and Austest in Sydney.

The NSTF includes an anechoic chamber, optics integration laboratories, process laboratories for high precision cleaning, a Class 1000 cleanroom with 2 tons crane and optical tables, a large thermal vacuum chamber, a vibration test facility, and mass properties measurement equipment for the centre of mass (CoM) and moments of inertia (MoI, principal axes only).

NSTF personnel have the relevant experience to perform spacecraft environmental qualification testing and have the necessary ESD and contamination control procedures. Other test houses may not be familiar with the stringent handling requirements of space hardware. High costs may be incurred if additional equipment is required and stricter process requirements are requested.

International travel to access overseas test facilities bears a significant risk of hardware damage during transport. It would incur additional personnel travel costs and an increased administrative burden regarding export/import control licenses.

6.5.3 Implementation options

The NSTF is the only facility of its kind in Australia. The co-location of all required integration and test facilities represents a significant advantage as it reduces the risk, cost, and administrative burden of coordinating multiple stakeholders.

Any tests that cannot be conducted at the NSTF and need to be performed elsewhere, such as shock testing, can be contracted to non-space specific test facilities if appropriate measures are taken to ensure the cleanliness of the spacecraft is maintained and handling of the spacecraft is performed appropriately. Expertise from NSTF could be used to support such tests to ensure appropriate measures are taken.

6.5.4 Element cost estimate

An estimated cost for OzFuel's environmental testing and launch is provided in Section 7. Note that the cost for qualification testing, acceptance testing, and launch of the platform is omitted as this is included in Skykraft's platform cost of AUD4M. Therefore, the only environmental testing costed is the qualification testing of the payload.

6.6 Ground stations

6.6.1 Description

The mission should utilise UHF/S-Band for TT&C (uplink/downlink) and S-Band/X-Band for science data transfer (downlink only). S-Band is sufficient for a demonstrator mission of this class, albeit at significantly reduced data volumes.

The procurement and implementation approaches could not be addressed in sufficient detail during the short timeframe of this study. Using existing Australian ground stations is possible; commercial providers are available.

6.6.2 Procurement approach aspects

The tenderer should handle the procurement of the ground station service. Commercial providers include:

- Amazon Web Services (AWS)
- Capricorn Space
- Cingulan Space
- Kongsberg Satellite Services (KSAT)
- LeafSpace
- Microsoft Azure
- RBC Signals
- Swedish Space Corporation (SSC)

A self-hosted station can be procured from:

- Safran
- ViaSat

6.6.3 Implementation options

The ground segment can be implemented in multiple ways. Ground stations can be procured and installed on-site by the customer, hosted on the customer's behalf at another facility, or rented in a time-share facility. Different ground stations may be used for TT&C and payload data; however, they are usually collocated. A common implementation is to have some level of customer-owned capability used for TT&C and a baseline amount of payload data downlink. Additional payload data downlink capacity can be purchased on an as-needs basis from commercial providers, allowing the ground segment to support a variable amount of payload data downlinking.

6.6.4 Element cost estimate

A ground station suitable for TT&C and payload data downlink hosted by the customer is likely to cost $200-500 k AUD, with an ongoing amount of $10k/month AUD for maintenance and system staffing. These figures are for a ground station with an appropriate level of availability for this mission; a lower cost option could be attained by reducing the system's robustness. This option is appropriate if guaranteed availability is required and is more cost-effective if multiple satellites are to be operated.

Commercial time-shared ground stations are available at $1-10USD/minute of activity. Both uplink and downlink capabilities are available. Assuming a 2,500km strip is imaged in each imaging orbit, 3.07 GB of compressed data is generated in each orbit (assuming 2:1 compression on 6.14 GB/orbit of sensor data). Each imaging orbit requires a downlink opportunity to transfer the data to the ground.

With a 600 second ground station pass (typical for the expected mission altitude), a downlink data rate of 41 Mbit/sec must be achieved. This is attainable with standard and commonly available X-Band radio systems. At three imaging orbits per day, the ground station access cost per day will be $300USD/day (3 passes * 10 minutes * $ 10 USD/minute). X-Band radio systems are commonly available with data rates of 100-520 Mbit/sec, which could be utilised to reduce the ground station access times and cost.

6.7 Processing pipeline and data distribution

Traditionally, raw sensor data is sent from the spacecraft to the ground segment, and specific processors (hardware and software) transform this data into higher-level data products. Generally, L0 and higher data processor modules are specific to the mission and need to be developed to work with the unique unprocessed payload data received from the spacecraft. It is unlikely that an existing compatible L0 data processor that meets the mission's requirements (OZF-M-19) could be procured. The re-use level depends on the payload's data format.

Based on previous studies (e.g., SCR), a traditional on-ground data processing pipeline development was estimated to cost approximately AUD 1.6M. However, as Australian missions are developed and commissioned, there might be an opportunity for the OzFuel mission to reuse other missions' data processing pipelines and infrastructure for a lower cost.

6.7.1 Procurement approach aspects

The L0 processor could be developed internationally or locally. The development of the L0 processor is a relative unknown if the work is performed locally, with more experience located internationally. L0 processors have been developed internationally for other missions, so a body of knowledge and experience can be drawn from them.

6.7.2 Implementation options

The implementation should adhere to or follow best-practice EO community standards for the L1, L2, and L3 data processors. Relevant standards may include ISO 19131[35], ISO 19112[36], ISO 19115[37], COG[38], STAC[39], and CARD4L[40].

Data outputs from each stage should be appropriately licensed to maximise the generated products' uptake (and thus national and international benefit). This may be achieved by licensing the data products under an 'open' license, such as CC BY[41]. Restrictive licensing may lower the acceptance and usage of the data products by organisations and consumers or act as a barrier to their usage.

6.7.3 Processing chain development

Mark Broomhall (GA) gave an overview to the study team on typical data generation processes and Australian activities in this area:

- GA develops L1 and L2 processors and currently runs a pipeline for L1 products from ESA and USGS systems.
- High-level generation is done via AWS (Amazon Web Services).
- Reflectance and NBAR are used in fuel load models - L2 products.
- L2 then move over from GA as a service to users for higher L3/L4 products.
- L3/L4 processing would occur at the customer site. For the OzFuel Pathfinder, raw data is required for science users, and L1 and higher processing could occur on the ground within the user community.

---

[35] https://www.iso.org/standard/71297.html
[36] https://www.iso.org/standard/70742.html
[37] https://www.iso.org/standard/53798.html
[38] https://www.cogeo.org/
[39] https://stacspec.org/
[40] https://ceos.org/ard/index.html#slide1
[41] https://creativecommons.org/licenses/by/4.0/

7 Mission preliminary cost estimate

This section presents a preliminary cost estimate of the OzFuel mission, from project kick-off to decommissioning.

For labour cost estimates, a program development duration of maximum 2 years from kick-off to FRR was assumed. This assumption is justified by the fact that the critical development activities are focused on interfacing the various payload subsystems (SAPHIRA, Rosella, TheMIS and Spiral Blue SE1) and optical design rather than platform design. A potentially shorter development time (1.5 year) could be envisaged if lead times allow.

Estimates for some activities (e.g., AIT) are based on UNSW Canberra Space's experience on the M2 programme at the NTSF.

An in-orbit life of two and a half years was assumed, including six months of LEOP and commissioning operations (requirement OZF-M-3).

Table 20 OzFuel preliminary mission development costs.

Mission Total Cost Breakdown		
Element	**Total Cost (AUD)**	**Notes**
Labour	$ 2,656,125.00	Primarily project management, payload development and operations.
Hardware	$ 5,291,400.00	Includes AUD4M for Skykraft services (platform, integration, acceptance testing, launch, and basic operations).
AIT	$ 217,000.00	Payload AIT only. Platform and system-level AIT included in Skykraft's platform services.
Launch	$ -	Included in Skykraft's platform services.
Operations - Ground Station	$ 350,000.00	AUD200k to AUD500k depending on provider.
Total	**$ 8,514,525.00**	
Margin	$ 851,452.50	10 per cent uncertainty margin
Grand Total	**$ 9,365,977.50**	

Note that the estimated costs exceed the 6 M AUD budget requirement (requirement OZF-M-2) by greater than 3.2 M AUD / 50%. A reduction in mission cost may be achieved by considering alternative platforms (the largest cost driver), sourcing lowest cost ground-station providers, and reducing the mission duration. However, assessment of these options is beyond the scope of this study.

The next pages show a more detailed cost breakdown of each of the examined mission costs.

Labour costs

Personnel	FTE pre-launch*	FTE post-launch^	Wage + On-costs per year	Total Cost (AUD)†	Notes
Project Management	1	0.25	$ 168,750.00	$ 210,937.50	Combined role; single person. Pre-launch: Full-time for 2 years. Post-launch: Full-time for 6 months of commissioning.
System Engineer	1	0.25	$ 155,250.00	$ 194,062.50	
Mechanical/ Thermal Engineer	1.5	0.5	$ 155,250.00	$ 310,500.00	Pre-launch: 1x Mechanical engineer for 1 year, 1x Thermal engineer for 6 months. Post-launch: 1x Thermal engineer for 6 months of commissioning.
Optical Engineer	1	0.25	$ 155,250.00	$ 194,062.50	Pre-launch: 1x engineer for 1 year. Post-launch: 0.5x engineer for 6 months of commissioning.
Instrument Scientist	1	0.5	$ 155,250.00	$ 232,875.00	Pre-launch: 1x scientist for 1 year. Post-launch: 1x scientist for 6 months of commissioning.
Electrical Engineer	2	0.25	$ 155,250.00	$ 349,312.50	Pre-launch: 1x engineer for 2 years. Post-launch: 1x engineer for 3 months (during commissioning).
Flight Software Engineer	2	1.5	$ 155,250.00	$ 543,375.00	Pre-launch: 1x engineer for 2 years. Post-launch: 1x engineer for 6 months of commissioning + 1 year of updates/patches.
AIT Engineer	0.5		$ 155,250.00	$ 77,625.00	Pre-launch: 1x engineer for 6 months prior to launch.
Operations	1	2.5	$ 155,250.00	$ 543,375.00	Pre-launch: 1x engineer for 1 year (operations preparation and support integrated systems testing). Post-launch: 1x engineer for 6 months of commissioning + 2 years of operations. (Skykraft provides basic operations services, but an operations engineer is required for detailed operations.)
Sub-Total	11	6		**$2,656,125.00**	

**Over 2-year duration*

^Over 2.5-year duration, including 6-month commissioning phase.

†*One Manager FTE = $168,750/year (including 35% on-costs), one Engineering FTE = $155,250/year (including 35% on-costs); based on a report by The Association of Professional Engineers Australia.*[42]

---

[42] *PROFESSIONAL ENGINEERS EMPLOYMENT AND REMUNERATION REPORT – 2020/2021. The Association of Professional Engineers Australia.*

Hardware Costs				
Component	**# Units**	**Cost per unit w/o margin (AUD)**	**Total Cost w/o margin (AUD)**	**Notes**
Payload:			**$1,291,400.00**	
Optical Assembly				Based on CHICO.
- Engineering Model	0.5	$150,000.00	$ 75,000.00	
- Flight Model	1	$350,000.00	$ 350,000.00	
Star Tracker	2	$193,200.00	$ 386,400.00	
Optical Bench	2	$ 25,000.00	$ 50,000.00	2 units: EM/STM & FM.
TheMIS	2	$ 75,000.00	$ 150,000.00	2 units: EM/Spare & FM.
FPA				Material, assembly, and testing costs. Development costs not considered.
Detector	2	$ -	$ -	In-kind expense
FEE/Rosella	1	$180,000.00	$ 180,000.00	EM from in-kind hardware. Need to purchase FM.
Spiral Blue processor	2	$ 50,000.00	$ 100,000.00	EM/Spare & FM.
Platform:			**$4,000,000.00**	Modified platform, integration, launch, and basic operations.
Sub-Total			**$5,291,400.00**	

Payload AIT Facility & Material Costs				
Component	**Duration (Days)**	**Cost (AUD/day)**	**Total Cost (AUD)**	**Notes**
FlatSat GSE	1		$ 1,000.00	
Optics AIT GSE	1	$ 100,000.00	$ 100,000.00	
Cleanroom Usage	0	$ 1,000.00	$ -	Provided via in-kind support.
Payload Environmental Testing:				
Qual. Vibration	3	$ 5,000.00	$ 15,000.00	Mt. Stromlo
Vibration Test Mounts	1	$ 3,000.00	$ 3,000.00	
Qual. Shock	1	$ 5,000.00	$ 5,000.00	External
Shock Test Mounts	1	$ 3,000.00	$ 3,000.00	
Qual. Thermal	10	$ 2,000.00	$ 20,000.00	Mt. Stromlo, Tenney; 2 weeks total.
Qual. Tvac + Tbal	5	$ 3,000.00	$ 15,000.00	Mt. Stromlo
Bake-Out	14	$ 3,000.00	$ 42,000.00	
Thermal Test Mounts	1	$ 3,000.00	$ 3,000.00	
FM Thermal Testing	5	$ 2,000.00	$ 10,000.00	
Accept. Vibration	1	$ -	$ -	Included in SkyKraft AUD4M cost.
Accept. Tvac + Tbal	5	$ -	$ -	Included in SkyKraft AUD4M cost.
Sub-Total			**$ 217,000.00**	

Launch Costs		
Element	**Total Cost (AUD)**	**Notes**
Launch	$ -	Included in SkyKraft AUD4M cost.
Dispenser	$ -	Included in SkyKraft AUD4M cost.
Logistics	$ -	Shipping and handling. Included in SkyKraft AUD4M cost.
Sub-Total	**$ -**	Note: Skykraft Skyride services are preferred, and cost is TBD

Ground Station Costs		
Element	**Total Cost (AUD)**	**Notes**
Ground Station	$200,000-500,000	Based on M2 costs. Depends on provider.
Sub-Total	**$200,000-500,000**	

8 Recommendations and open points

The study concluded with the following recommendations for future work:

1. Refine the conceptual design of the space and ground segments and develop a better cost model and estimates.
2. Develop and refine risk statements and mitigation strategies.
3. Expand and clarify aspects of the preliminary model philosophy development.
4. Define project organisation and management roles, responsibilities, and logistics to reduce risk (particularly in AIT).
5. Formalise links and differences between the OzFuel Pathfinder and future generation systems.
6. Refine the power budget with inputs from a more detailed ConOps and instrument power consumption profile.
7. Define the high-speed interface between Rosella and Spiral Blue's Space Edge computer.
8. Review temperature requirements for the payload's fore-optics and structure.
9. Determine the required optical breadboard mass and design.
10. Review the placement of the thermal stop in the payload.
11. Codify sensor parameters and values used in the instrument performance models based on the ConOps and image acquisition modes.
12. Refine links between science parameters and instrument performance requirements.
13. Refine the pointing budget in conjunction with image quality requirements and science goals.

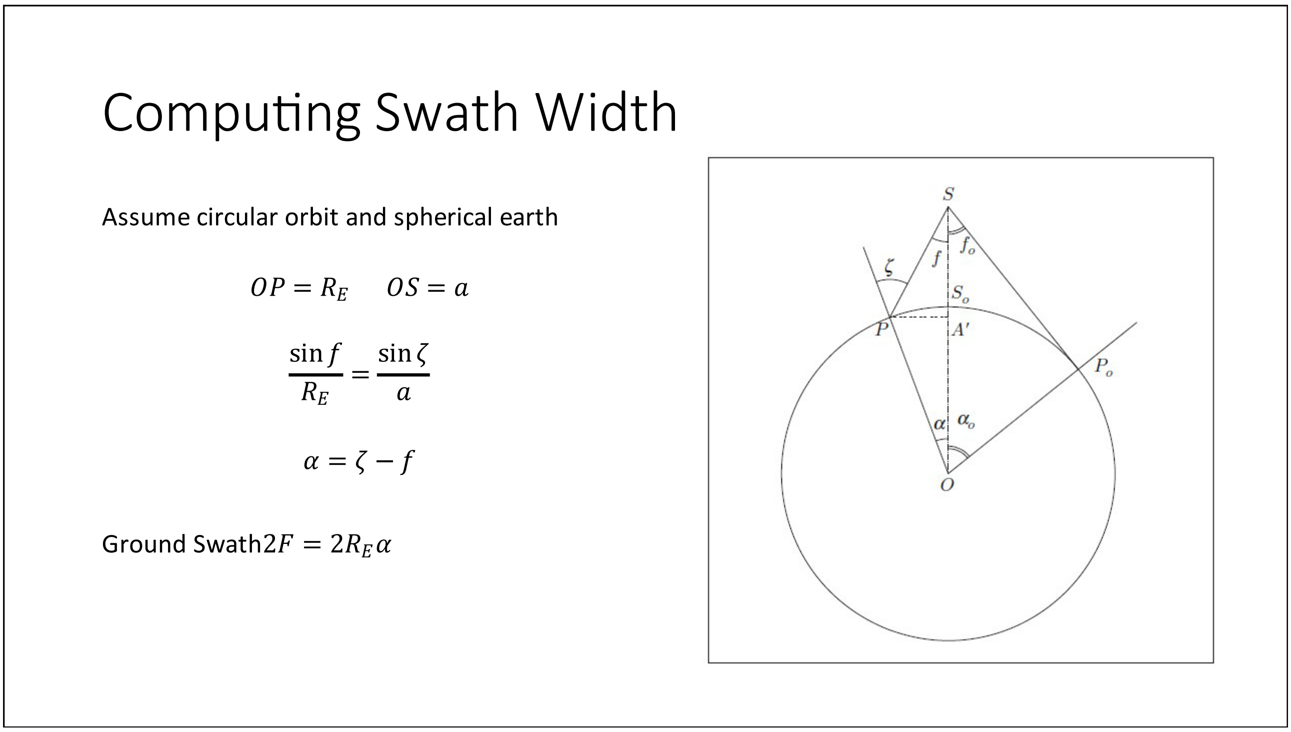
9 Appendix A: Study participants

The list of experts involved in or consulted as part of the study is presented in the table below.

Table 21: List of personnel involved in the study

Organisation	Name	Role
ANU Institute for Space Systems	Alexy Grigoriev Annino Vaccarella Brian Taylor David Chandler Israel Vaughn James Gilbert Jamie Ward Jia Urnn Lee Joice Mathew Marta Yerba Nicolas Younes Robert Sharp	Study sponsors and domain expertise
Skykraft Pty. Ltd.	Doug Griffin	Satellite bus provider
University of Melbourne	Clint Therakam Simon Barraclough	Customer technical support and thermal management system design
Spiral Blue	Taofiq Huq	Image data processing/machine learning and image processor module provider
Geoscience Australia	David Hudson Mark Broomhall	Project support Data product generation
UNSW Canberra Space	Anthony Kremor Denis Naughton Igor Dimitrijevic Jai Vennik Melrose Brown Miriam Lim Ryan Jefferson Samuel Boland Steve Gehly Tarik Errabih	Mission design and domain expertise

10 Appendix B: Orbit analysis summary slide deck



Computing Swath Width

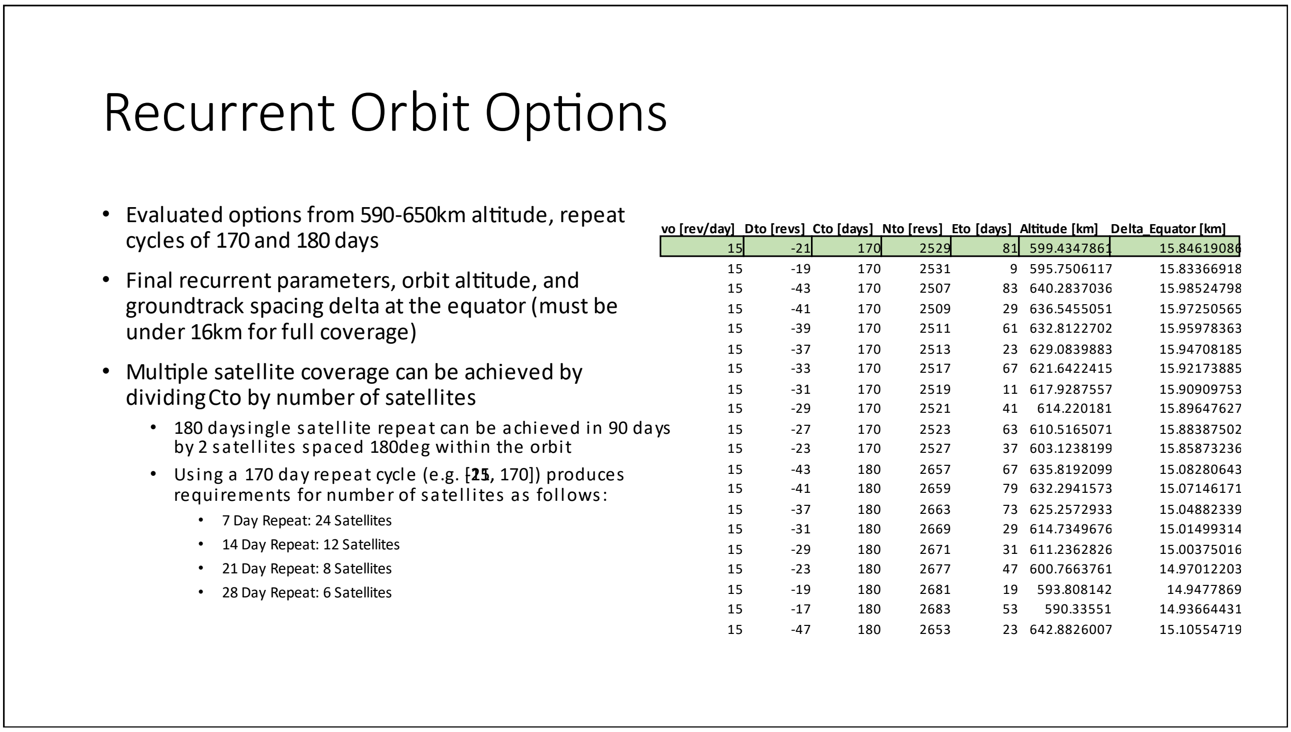
Assume circular orbit and spherical earth

$$OP = R_E \qquad OS = a$$

$$\frac{\sin f}{R_E} = \frac{\sin \zeta}{a}$$

$$\alpha = \zeta - f$$

Ground Swath $2F = 2R_E\alpha$



Recurrent Orbit Options

- Evaluated options from 590-650km altitude, repeat cycles of 170 and 180 days
- Final recurrent parameters, orbit altitude, and groundtrack spacing delta at the equator (must be under 16km for full coverage)
- Multiple satellite coverage can be achieved by dividing Cto by number of satellites
    - 180 day single satellite repeat can be achieved in 90 days by 2 satellites spaced 180deg within the orbit
    - Using a 170 day repeat cycle (e.g. [15, -21, 170]) produces requirements for number of satellites as follows:
        - 7 Day Repeat: 24 Satellites
        - 14 Day Repeat: 12 Satellites
        - 21 Day Repeat: 8 Satellites
        - 28 Day Repeat: 6 Satellites

vo [rev/day]	Dto [revs]	Cto [days]	Nto [revs]	Eto [days]	Altitude [km]	Delta_Equator [km]
15	-21	170	2529	81	599.4347861	15.84619086
15	-19	170	2531	9	595.7506117	15.83366918
15	-43	170	2507	83	640.2837036	15.98524798
15	-41	170	2509	29	636.5455051	15.97250565
15	-39	170	2511	61	632.8122702	15.95978363
15	-37	170	2513	23	629.0839883	15.94708185
15	-33	170	2517	67	621.6422415	15.92173885
15	-31	170	2519	11	617.9287557	15.90909753
15	-29	170	2521	41	614.220181	15.89647627
15	-27	170	2523	63	610.5165071	15.88387502
15	-23	170	2527	37	603.1238199	15.85873236
15	-43	180	2657	67	635.8192099	15.08280643
15	-41	180	2659	79	632.2941573	15.07146171
15	-37	180	2663	73	625.2572933	15.04882339
15	-31	180	2669	29	614.7349676	15.01499314
15	-29	180	2671	31	611.2362826	15.00375016
15	-23	180	2677	47	600.7663761	14.97012203
15	-19	180	2681	19	593.808142	14.9477869
15	-17	180	2683	53	590.33551	14.93664431
15	-47	180	2653	23	642.8826007	15.10554719

Simulation Study – Long Repeat Cycle w Slew

- Evaluate 550km recurrent sun-synchronous orbit with cross-track slew capability
  - 170 day repeat cycle
  - Actual altitude 548km
  - 16km ground swath
- The 16km swath corresponds to a 1.67 deg field of view at 548km
  - Assume we are additionally able to slew in cross track by small amount, evaluate contact opportunities at single location (National Arboretum, Canberra)
  - With 0 slew, satellite needs to be at 89.1 deg elevation relative to site to see it
  - At 20 deg slew, satellite only needs to be at 67.3 deg elevation relative to site to see it

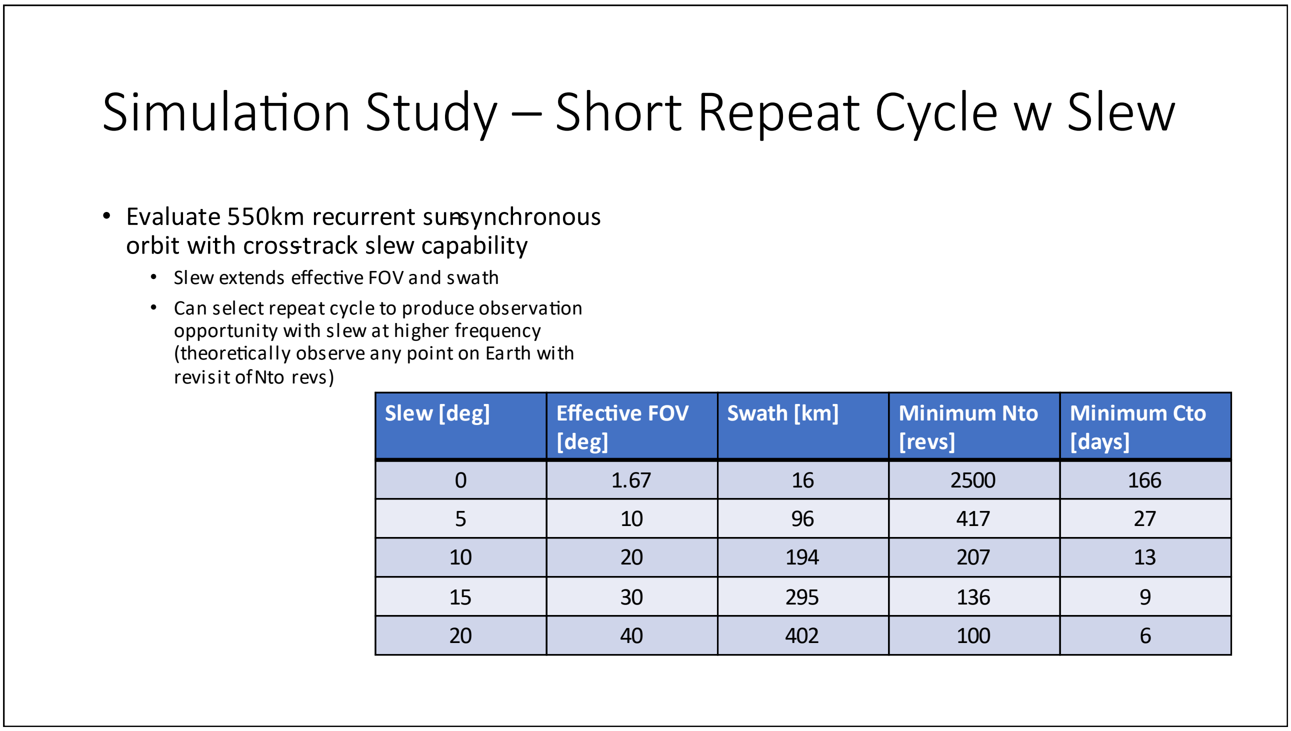
vo [rev/day]	Dto [revs]	Cto [days]	Nto [revs]	Eto [days]	Altitude [km]	Delta_Equator [km]
15	7	170	2557	73	548.2939312	15.6726698

- Orbit Parameters
  - SMA: 6926.43 km
  - ECC: 0.001
  - INC: 97.586 deg
  - RAAN: 358.3 deg
  - AOP: 0 deg
  - TA: 0 deg
  - UTC: 2022-02-22 13:30:00

Nto= Cto*vo + Dto

Simulation Study – Long Repeat Cycle w Slew

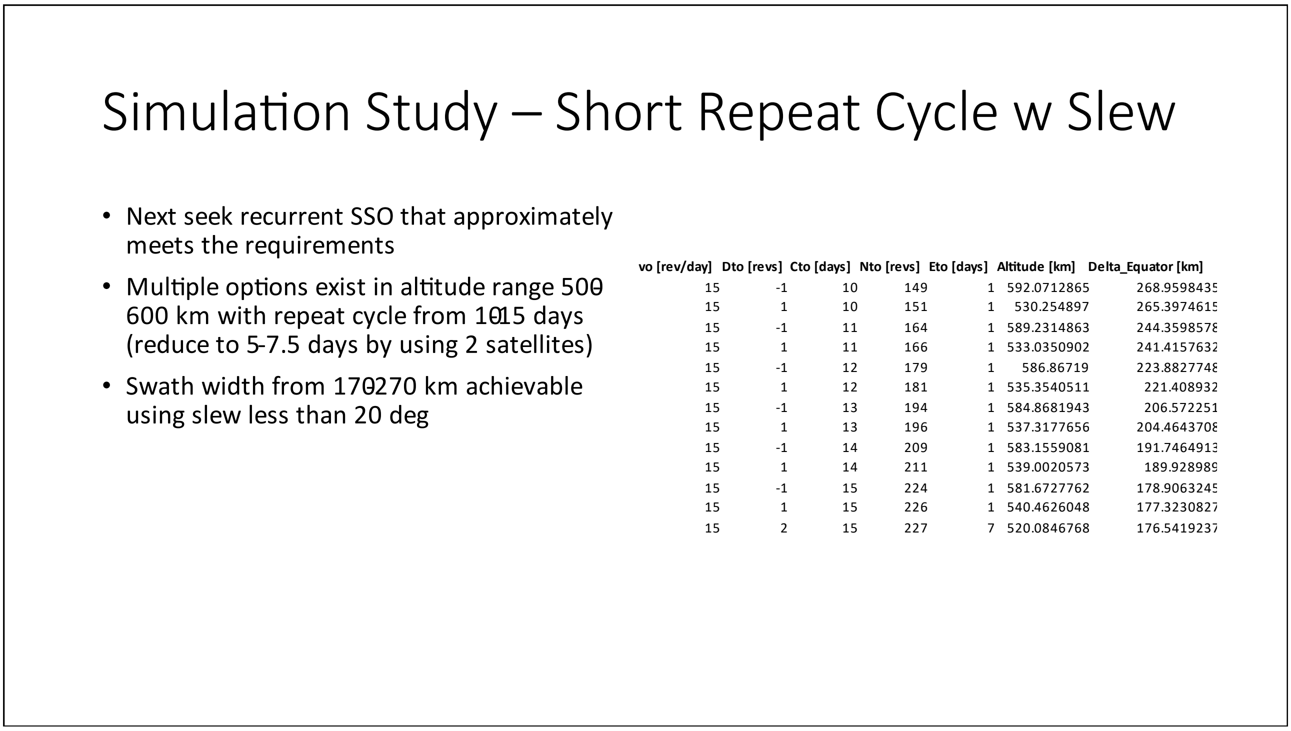
- In first 24 hours, there are 4 passes where OzFuel is above the horizon, but none above 67 deg elevation to achieve observation with 20 deg slew (also 2 occur at night)
- In 90 days, following results obtained
  - 20 deg slew (67.3 deg el): 16 contacts
  - 15 deg slew (72.8 deg el): 12 contacts
  - 10 deg slew (78.2 deg el): 10 contacts
  - 5 deg slew (83.7 deg el): 3 contacts
  - 0 deg slew (89.1 deg el): 0 contacts



Simulation Study – Short Repeat Cycle w Slew

- Evaluate 550km recurrent sun-synchronous orbit with cross-track slew capability
  - Slew extends effective FOV and swath
  - Can select repeat cycle to produce observation opportunity with slew at higher frequency (theoretically observe any point on Earth with revisit of Nto revs)

Slew [deg]	Effective FOV [deg]	Swath [km]	Minimum Nto [revs]	Minimum Cto [days]
0	1.67	16	2500	166
5	10	96	417	27
10	20	194	207	13
15	30	295	136	9
20	40	402	100	6



Simulation Study – Short Repeat Cycle w Slew

- Next seek recurrent SSO that approximately meets the requirements
- Multiple options exist in altitude range 500-600 km with repeat cycle from 10-15 days (reduce to 5-7.5 days by using 2 satellites)
- Swath width from 170-270 km achievable using slew less than 20 deg

vo [rev/day]	Dto [revs]	Cto [days]	Nto [revs]	Eto [days]	Altitude [km]	Delta_Equator [km]
15	-1	10	149	1	592.0712865	268.9598435
15	1	10	151	1	530.254897	265.3974615
15	-1	11	164	1	589.2314863	244.3598578
15	1	11	166	1	533.0350902	241.4157632
15	-1	12	179	1	586.86719	223.8827748
15	1	12	181	1	535.3540511	221.408932
15	-1	13	194	1	584.8681943	206.572251
15	1	13	196	1	537.3177656	204.4643708
15	-1	14	209	1	583.1559081	191.7464913
15	1	14	211	1	539.0020573	189.928989
15	-1	15	224	1	581.6727762	178.9063245
15	1	15	226	1	540.4626048	177.3230827
15	2	15	227	7	520.0846768	176.5419237

Recurrence and Swath Summary

Definitions and Nomenclature

Recurrence triple defined by [vo, Dto, Cto]; $\mathrm{Nto} = \mathrm{Cto} * \mathrm{vo} + \mathrm{Dto}$

vo = whole number of nodal revolutions per day (rounded)

Cto = whole number of days before repeat

Nto = whole number of nodal revolutions before repeat

Eto = whole number of days until ground track is δ from original ground track

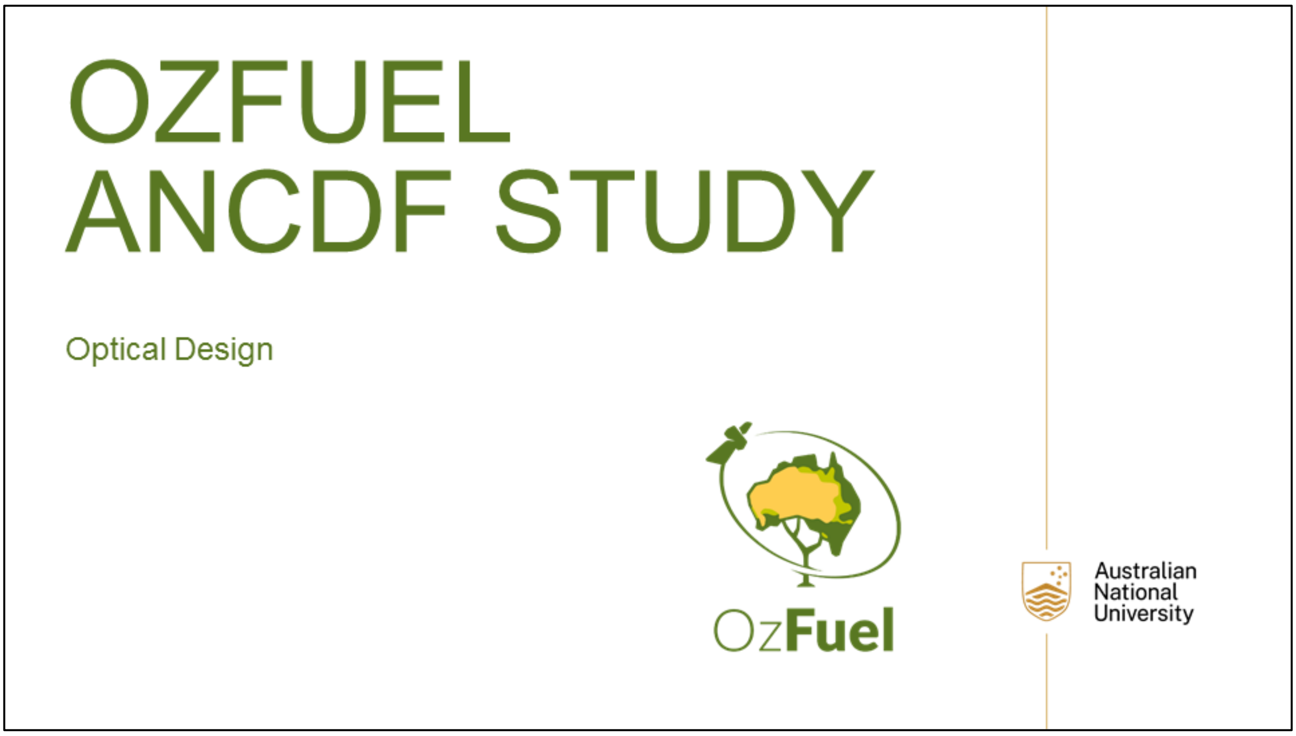
$\delta = \frac{360°}{Nto}$ = spacing between groundtracks over whole cycle (at Equator)

R and D subscripts for spacing on consecutive revs, days

Design Notes

- Require $\delta <$ swath to achieve global coverage with no gaps. For a given swath, this will place lower limit on Nto and therefore Cto given the altitude requirements.
- Assuming swath of 16km requires $\delta < 16/\mathrm{Re}$ yields Nto = 2505 revs for full coverage.
- At 600km altitude (14.9 rev/day), this would require at least 168 days in the repeat cycle for a single satellite (further details on options for recurrent triples follow).
- Best practice is to avoid Eto = 1 to move more regularly through the coverage pattern instead of each consecutive day putting ground track right next to previous day

11 Appendix C: OzFuel optical system design and analysis

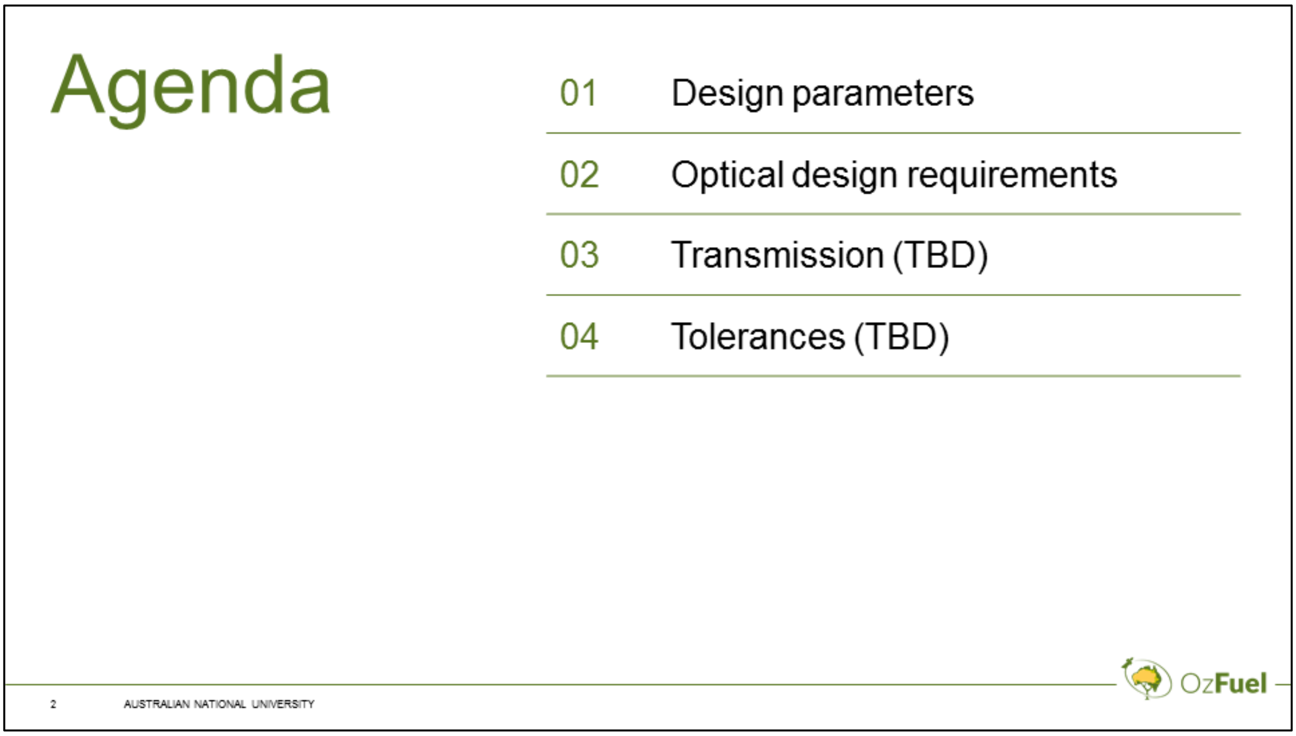


OZFUEL ANCDF STUDY

Optical Design

OzFuel

Australian
National
University



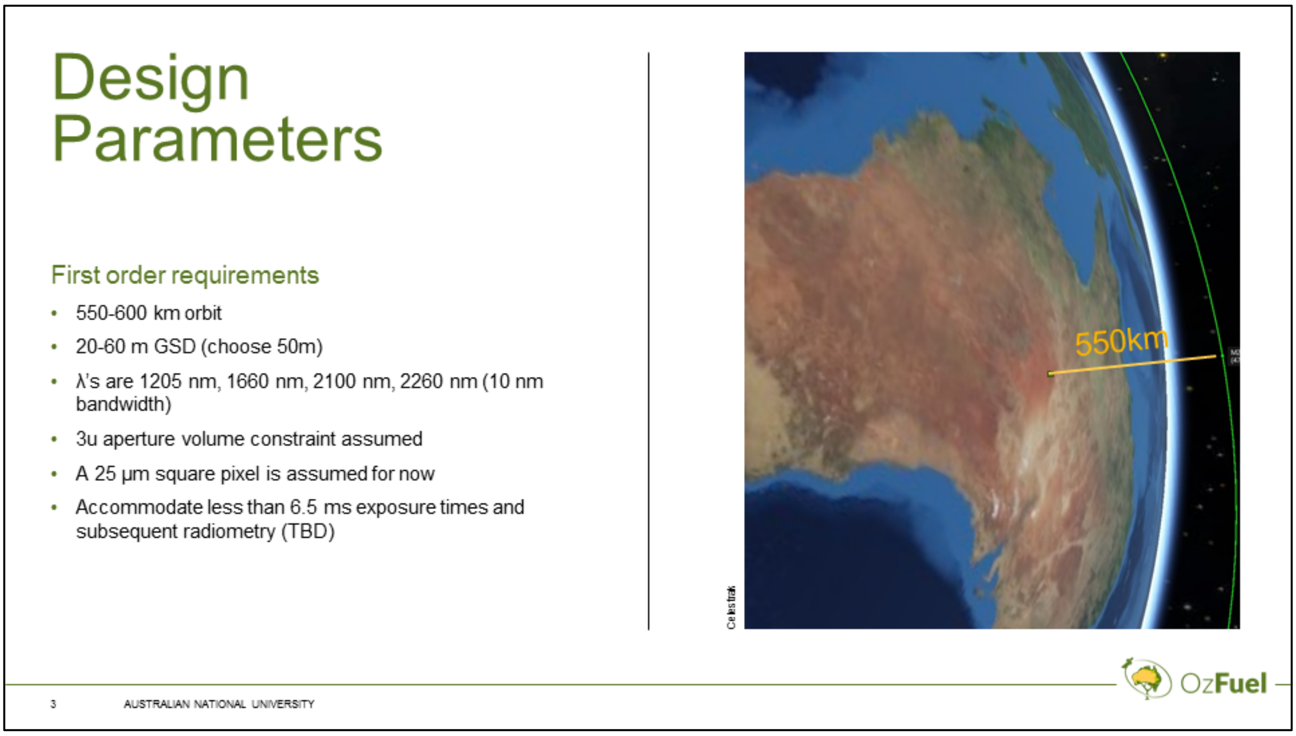
Agenda

01 Design parameters

02 Optical design requirements

03 Transmission (TBD)

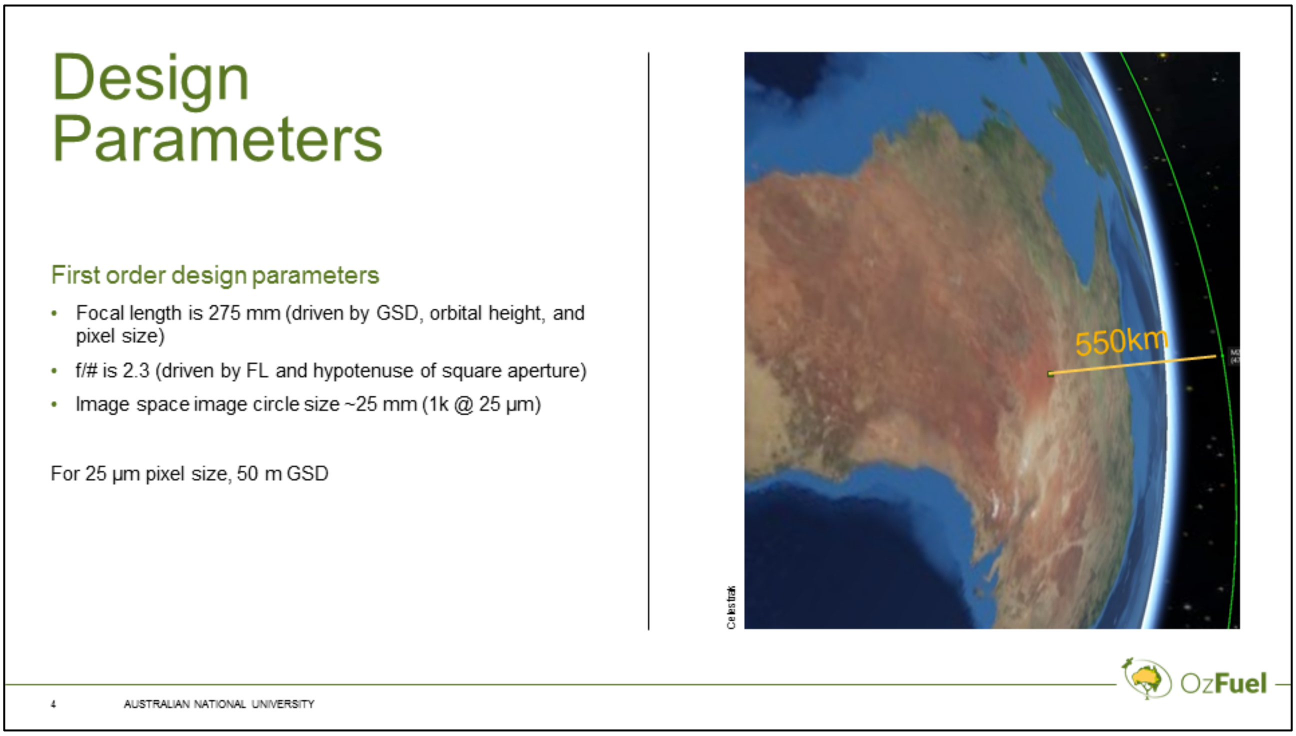
04 Tolerances (TBD)



Design Parameters

First order requirements

- 550-600 km orbit
- 20-60 m GSD (choose 50m)
- λ's are 1205 nm, 1660 nm, 2100 nm, 2260 nm (10 nm bandwidth)
- 3u aperture volume constraint assumed
- A 25 µm square pixel is assumed for now
- Accommodate less than 6.5 ms exposure times and subsequent radiometry (TBD)



Design Parameters

First order design parameters

- Focal length is 275 mm (driven by GSD, orbital height, and pixel size)
- f/# is 2.3 (driven by FL and hypotenuse of square aperture)
- Image space image circle size ~25 mm (1k @ 25 µm)

For 25 µm pixel size, 50 m GSD

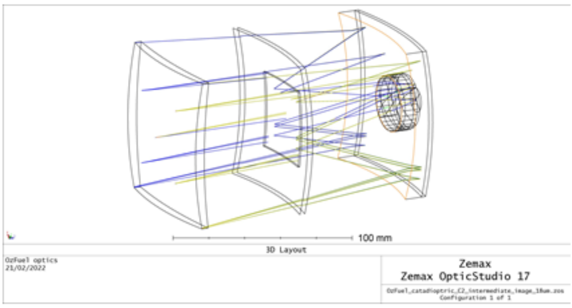
Design Parameters @ 50 m GSD

	SAPHIRA HgCdTe	ME1120(NEW) 512x512	H2RG HgCdTe	ORION InSb
Array Format	320x246	512x512	2048x2048	2048x2048
Pixel Pitch	24 µm	24 µm	18 µm	25 µm
FL for 50 m GSD	264 mm	264 mm	198 mm	275 mm
Image circle ø	~10 mm	17.5 mm	52.5 mm	72.5 mm
f/#	2.2	2.2	1.65	2.3

Optical Design

First order design parameters

- Focal length is 264-275 mm (driven by GSD, orbital height, and pixel size)
- f/# is 1.65-2.3 (driven by FL and long side of square aperture)



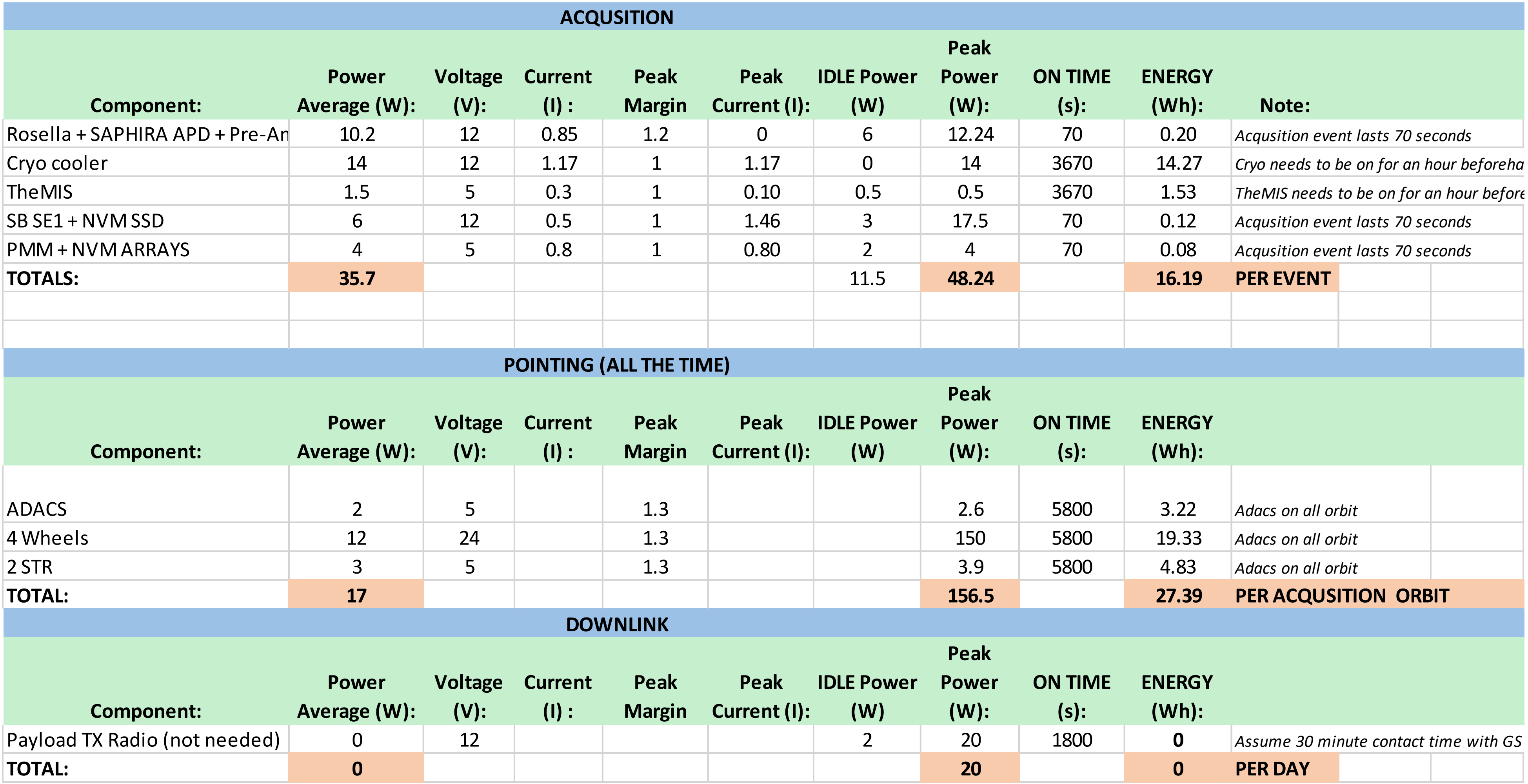
12 Appendix D: OzFuel preliminary mass budget

Description	Parent Assembly	Supplier/ Manufacturer	Qty	Estimated Unit Mass (g)	Margin (%)	Unit Margin (g)	Total Mass (g)	Material	Reference	Volume (mm3)	Material Density (kg/m3)
Payload	**OzFuel**	Consortium	**1**	**11469.5**		**1654.7**	**13124.2**				
Payload Optics	Payload	ANU	1	**2000**		**400.0**	2400.0				
Foreoptics	Payload optics	ANU	1	500.0	20%	100.0	600.0		Used OZF preliminary optical design estimates		
Corrective optics module	Payload optics	ANU	1	500.0	20%	100.0	600.0				
Structures	Payload optics	ANU	1	1000.0	20%	200.0	1200.0				
Payload Mechanical	Payload	TBD	1	**5600**		**685.0**	6285.0				
Payload Bay Structure	Payload Mechanical	Skykraft	1	2900.0	5%	145.0	3045.0	Aluminium	Based on current measured values		
Optical Bench incl blades/iso-mounts	Payload Mechanical	TBD	1	2700.0	20%	540.0	3240.0	Titanium		600000	4500
Payload Thermal Control (TheMIS)	Payload	UoM	1	**2369.5**		**269.7**	2639.2				
Cryocooler	TheMIS	Thales	1	1050.0	5%	52.5	1102.5		Thales LSF9987		
Cooler Structure	TheMIS	UoM	1	250.0	10%	25.0	275.0	Aluminium	From SpIRIT		
Cooler Electronics	TheMIS	UoM	1	217.0	10%	21.7	238.7		Measured from SpIRIT + estimate for housing		
Cooler Thermal Strap	TheMIS	UoM	1	51.0	20%	10.2	61.2	Copper	Estimate	6000	8500
Radiator Fins	TheMIS	UoM	20	24.3	20%	4.9	583.2	aluminium	Estimate	9000	2700
MLI	TheMIS	UoM	1	315.5	20%	63.1	378.6	Mylar	Estimate	228600	1380

Description	Parent Assembly	Supplier/ Manufacturer	Qty	Estimated Unit Mass (g)	Margin (%)	Unit Margin (g)	Total Mass (g)	Material	Reference	Volume (mm3)	Material Density (kg/m3)
Payload Electronics	Payload	ANU	1	**1500**		**300.0**	**1800.0**				
Rosella (APD, Preamp, FPGA, ADC, bias)	Payload Electronics	ANU	1	750.0	20%	150.0	900.0	aluminium + PCBs			
Space Edge 1	Payload Electronics	Spiral Blue	1	250.0	20%	50.0	300.0				
Payload Management Module	Payload Electronics	UNSW?	1	250.0	20%	50.0	300.0				
Payload Radio (S-Band)	Payload Electronics	UNSW?	1	150.0	20%	30.0	180.0				
Harness	Payload Electronics	ANU?	1	100.0	20%	20.0	120.0		Allocation		
Platform	**OzFuel**	Skykraft	**1**	**20340.0**		**1027.0**	**21367.0**				
Avionics	Platform	Skykraft	1	2000.0		100.0	2100.0				
Avionics Bay	Platform	Skykraft	1	1100	5%	55.0	1155.0		Based on current measured values		
Faceboards	Platform	Skykraft	1	900	5%	45.0	945.0		Based on current measured values		
ADCS	Platform		1	4220		211.0	4431.0				
ADCS Module (Blue Canyon Flex Core; integrated with 2x Magnetorquers, integrated Limb sensors TBC)	ADCS	COTS	1	520	5%	26.0	546.0		TBC		
Reaction Wheels (RW-1)	ADCS	COTS	4	750	5%	37.5	3150.0		TBC		
Star Trackers (Standard NST)	ADCS	COTS	2	350	5%	17.5	735.0		TBC		

Description	Parent Assembly	Supplier/ Manufacturer	Qty	Estimated Unit Mass (g)	Margin (%)	Unit Margin (g)	Total Mass (g)	Material	Reference	Volume (mm3)	Material Density (kg/m3)
EPS	Platform	Skykraft	1	4020		201.0	4221.0				
Solar Panel Assembly	EPS	Skykraft	1	1800	5%	90.0	1890.0	misc.	Based on current measured values		
Batteries	EPS	Skykraft	1	1400	5%	70.0	1470.0	misc.	Based on current measured values		
SA Drive Mech	EPS	Skykraft	1	820	5%	41.0	861.0	misc.	Based on current measured values		
Structure	Platform	Skykraft	1	10100		515.0	10615.0				
Primary Structure	Structure	Skykraft	1	8000	5%	400.0	8400.0	Aluminium	Based on current measured values		
Chassis Struts	Structure	Skykraft	1	1900	5%	95.0	1995.0	Aluminium	Based on current measured values		
Fasteners	Structure	Skykraft	1	200	10%	20.0	220.0		Allocation based on Heritage		
Total				**31809.5**		**2681.7**	**34491.2**				
Total + system margin					**10 %**	**3449.1**	**37940.3**				

13 Appendix E: OzFuel preliminary power budget



ACQUSITION

Component:	Power Average (W):	Voltage (V):	Current (I) :	Peak Margin	Peak Current (I):	IDLE Power (W)	Peak Power (W):	ON TIME (s):	ENERGY (Wh):	Note:
Rosella + SAPHIRA APD + Pre-An	10.2	12	0.85	1.2	0	6	12.24	70	0.20	*Acqusition event lasts 70 seconds*
Cryo cooler	14	12	1.17	1	1.17	0	14	3670	14.27	*Cryo needs to be on for an hour beforeha*
TheMIS	1.5	5	0.3	1	0.10	0.5	0.5	3670	1.53	*TheMIS needs to be on for an hour before*
SB SE1 + NVM SSD	6	12	0.5	1	1.46	3	17.5	70	0.12	*Acqusition event lasts 70 seconds*
PMM + NVM ARRAYS	4	5	0.8	1	0.80	2	4	70	0.08	*Acqusition event lasts 70 seconds*
TOTALS:	**35.7**					11.5	**48.24**		**16.19**	**PER EVENT**

POINTING (ALL THE TIME)

Component:	Power Average (W):	Voltage (V):	Current (I) :	Peak Margin	Peak Current (I):	IDLE Power (W)	Peak Power (W):	ON TIME (s):	ENERGY (Wh):	
ADACS	2	5		1.3			2.6	5800	3.22	*Adacs on all orbit*
4 Wheels	12	24		1.3			150	5800	19.33	*Adacs on all orbit*
2 STR	3	5		1.3			3.9	5800	4.83	*Adacs on all orbit*
TOTAL:	**17**						**156.5**		**27.39**	**PER ACQUSITION ORBIT**

DOWNLINK

Component:	Power Average (W):	Voltage (V):	Current (I) :	Peak Margin	Peak Current (I):	IDLE Power (W)	Peak Power (W):	ON TIME (s):	ENERGY (Wh):	
Payload TX Radio (not needed)	0	12				2	20	1800	**0**	*Assume 30 minute contact time with GS*
TOTAL:	**0**						**20**		**0**	**PER DAY**

Assuming Skykraft Block 2 Platform:								
		Cell Number	**Capacity (Ah)**	**Nominal V**				
Platform Battery (total)		**42**	3.4	3.6	142.8	Ah	**Energy:**	
	String 1	21	3.4	75.6	71.4	Ah	257.04	Wh
	String 2	21	3.4	75.6	71.4	Ah	257.04	Wh
Platform Solar Array	**Assuming Spectrolab UTJ Cells**							
	Number cells:		90	cells				
	area		27.22	cm^2				
	Imp(a)		0.018	A/cm^2				
	Vmp		2.4	V				
	Imp		0.48996	A				
	AM0		1384.7	W/m^2				
	Max Current		0.48996					
	Efficiency		0.3					
	Watts per cell		1.175904	W				
	90 cells		105.8314	W				
	Margin		0.5	Includes eclipse (1/3 orbit) and off sun pointing				
	Power Actual		52.91568	watts	orbit of 5800 sec			
	Energy / orbit		**85.25304**	Wh/orbit				

orbits/day	adacs						
15	27.39	410.8333	Wh	Adacs ON every orbit			
	acq						
2	16.19	32.38833	Wh	Two acqusition orbits per day			
	Dlink						
2	0	0	Wh	Two 15 minute radio TX events per day			
TOTAL DAY CONSUMED PLOAD:		**443.2217**	**Wh**				
TOTAL DAY PRODUCED:		**1278.796**	**Wh**				
Surplus Energy per day:		**835.5739**	**Wh**	**55.7049289**	**Wh/orbit**		
Platform POWER CONSUMPTION			**Power (w)**	**Orbit (s)**	**Wh/Orbit**		
			10	5800	**16.11111**		

14 Appendix F: OzFuel Risk register

See Section 5.60 for detailed risk classification. Likelihood: A(unlikely) – E (certain) Severity: 1 (minor) – 5 (catastrophic)

ID	Risk	Likelihood	Severity	Impact Level	Impact Severity	Mitigation Approach
OZF-R-1	Launch failure	B	5	B5	HIGH	Procure launch service from an established provider with a good track record. Accept/Carry the risk.
OZF-R-2	Delays in long lead items procurement	E	3	E3	HIGH	Procure long lead items as early as possible (optical, electronic, mechanical components and ground support equipment).
OZF-R-3	Late program stage systems failures (e.g., in PFM vibe)	C	4	C4	HIGH	Determine launch environmental parameters early in the program to ensure hardware compatibility and reduce the probability of system failure.
OZF-R-4	Detector contamination during AIT	C	4	C4	HIGH	Develop robust contamination control procedures. e.g., design heater units for detector bakeout.
OZF-R-5	Leak in cryocooler during operations	B	5	B5	HIGH	Understand cryocooler operational, environmental, and logistic requirements to reduce the probability of failure.
OZF-R-6	Unavailability or loss of key staff as needed during the programme	C	4	C4	HIGH	Have a contingency plan to address staff departure/unexpected losses.
OZF-R-7	Work package ambiguity and lack of communication among consortium members	C	4	C4	HIGH	Maintain regularly scheduled communications with consortium members.
OZF-R-8	Instrument design does not meet performance requirements and does not represent the OzFuel mission requirement	B	5	B5	HIGH	Develop a robust and detailed AIT Plan early in the program to ensure performance requirements are met and maintained.
OZF-R-9	On-orbit performance degradation below science requirements	B	5	B5	HIGH	Where possible, design, procure and test hardware/software to not only meet, but exceed scientific requirements without affecting the integrity, quality, and endurance of said hardware/software.
OZF-R-10	Misalignment of project goals with stakeholder needs	C	5	C5	HIGH	Hold regularly scheduled meetings with stakeholders.
OZF-R-11	Undiagnosable hardware or software problems during	B	5	B5	HIGH	Development of FlatSat digital twin to aid design, testing and on-orbit ops/debugging/anomaly resolution.

ID	Risk	Likelihood	Severity	Impact Level	Impact Severity	Mitigation Approach
	operations resulting in mission failure					
OZF-R-12	Unforeseen technical challenges during the development of Rosella causing delays or budget slip	D	4	D4	HIGH	Maintain regular contact with the Rosella design team to ensure timely communication of potential issues so that overall program objectives can be adjusted and communicated to appropriate stakeholders.
OZF-R-13	Critical components damaged or destroyed during handling	c	4	C4	HIGH	Proper handling procedures, spares and staff training.
OZF-R-14	Delays in the software development process	D	4	D4	HIGH	Develop a rigorous progress review process and procedures.
OZF-R-15	Insufficient AIT schedule	C	4	C4	HIGH	An AIT Plan, which forms one of the major inputs to the project schedule, must provide a regular basis for customer review and evaluation.
OZF-R-16	Mission capability scope creep	C	4	C4	HIGH	Identify and fix primary objectives early on in the program.
OZF-R-17	Space debris causes damage to spacecraft	A	5	B5	HIGH	Avoid crowded orbits (e.g., Starlink constellation). Accept/carry the risk.
OZF-R-18	Quality control issues on the part of the PCB manufacturer and/or assembler cause one or more flight model PCBs to be unusable	C	4	C4	HIGH	Develop robust AIT procedures that follow "Test like you fly" conditions to ensure the quality of the product and the quality of results.
OZF-R-19	Subsystem design, AIT errors resulting in on-orbit failure	B	4	B4-5	HIGH	Develop an AIT plan early in the program showing a clear distinction between the development and qualification stages of the AIT process, and follow a strict "Test like you fly" process during the qualification phase of the program.
OZF-R-20	Incorrect specification of long lead items	C	3	C3	MEDIUM	Identify long lead items early on in the program and prioritise their specifications.
OZF-R-21	Radiation susceptibility of components prevents nominal operations	C	3	C3	MEDIUM	Choose components and glasses appropriate to the mission duration and radiation environment.
OZF-R-22	Thermal balance on orbit has a negative margin	B	4	B4	MEDIUM	Extensive thermal testing and characterization of TheMIS, the payload and the integrated spacecraft.

ID	Risk	Likelihood	Severity	Impact Level	Impact Severity	Mitigation Approach
OZF-R-23	Unable to obtain ground truth within requirements	B	4	B4	MEDIUM	Ground-based testing to validate calibration parameters and procedures.
OZF-R-24	Unavailability of science-level requirements before program kick-off	B	4	B4	MEDIUM	Ensure key science requirements are accurately determined and stated before kick-off.
OZF-R-25	Pointing jitter requirement not met on orbit impacting image quality	B	4	B4	MEDIUM	Source a flight-proven ADCS subsystem that meets pointing requirements.
OZF-R-26	EMI and EMC impacts between EPS and other subsystems on the payload performance	B	4	B4	MEDIUM	Extensive system-level testing.
OZF-R-27	LWIR cross-talk in SWIR filter profiles or stray light impact sensor performance	B	3	B3	MEDIUM	Extensive testing and characterization.
OZF-R-28	Misalignment of optical components during launch and on-orbit due to thermal loads	B	4	B4	MEDIUM	Design to expected loads, extensive testing.
OZF-R-29	The baselined platform does not meet performance requirements	C	3	C3	MEDIUM	Test as you fly. Skykraft launch Q3 2022 increases TRL.
OZF-R-31	Orbit injection failure or misplaced insertion resulting in an incorrect orbit that could degrade science objectives	C	3	C3	MEDIUM	Accept/carry the risk.
OZF-R-32	Bush fire season is not representative of typical seasons	B	2	B2	LOW	Accept/carry the risk.
OZF-R-33	Cloud cover over key sites (ROI and calibration sites) limits acquired data volume	B	2	B2	LOW	Accept/carry the risk.

UNSW CANBERRA | Space

UNSW Canberra at the
Australian Defence Force Academy
Northcott Drive, Canberra ACT 2600

space.unsw.adfa.edu.au

@UNSWCanberra
@UNSWCanberra
@UNSWCanberra
@UNSWCanberra
@UNSWCanberra

CRICOS No. 00098G
990391422