Technical Feasibility Study into Australian Development of a Satellite Cross-Calibration Radiometer (SCR) series including potential to support partner land imaging programs

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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

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Technical Feasibility Study into Australian Development of a Satellite Cross-Calibration Radiometer (SCR) series including potential to support partner land imaging programs

12

Satellite Cross-Calibration Radiometer Feasibility

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1 Executive brief

- A preliminary design study was conducted to determine the technical feasibility of the Satellite Cross-Calibration Radiometer mission.

- The **Satellite Cross-Calibration Radiometer (SCR) mission** provides:
  - an opportunity to secure Australia's data supply for Earth observations;
  - considerable space utilisation/data quality benefits; and
  - a pathway to develop the Australian space sector, including manufacturing.

- This work represents the **12th study conducted at UNSW Canberra Space's Australian National Concurrent Design Facility** and was performed with support from Geoscience Australia, the Australian Space Agency and CSIRO.

- From December 2020 to March 2021 a total of 40 experts from 13 organisations were consulted or participated in the study.

- The NASA/USGS (United States Geological Survey) Landsat programme provides a critical dataset to Australia. Australian users are also making increasing use of this data alongside data from other foreign government programs and commercial operators. This study explores opportunities for uplifting Australian capability and contribution to the US land imaging program as well as other partner land imaging programs.

- The study found the **SCR mission is technically and programmatically feasible**. While no Commercial off the Shelf (COTS) option exists for the whole system, the complexity of the mission is feasible for the current capabilities within the global and Australian space sector.

- The **space components to design, build, launch and fly a single SCR mission would cost approximately AUD36M**, in the 25-150kg weight class and take ~2 years to develop. In addition to contract management functions, the **mission owner would undertake ground station operations, maintain ground calibration networks and utilisation activities like data processing and distribution** outside of the above costing.

- The value of the missions to Australia and key partners would be maximised by aligning to the timelines of the NASA's CLARREO Pathfinder mission starting at the end of 2023. However, the mission will still deliver the intended effects if this is not possible. To align with CLARREO, the SCR pathfinder missions would need to be initiated within 2021.

- The study identified four specific satellite subsystems that do not exist today on the commercial market. These represent an opportunity to support an SCR mission and hold export potential.

- The study developed two options for further development:
  - Option A: delivering the satellite cross-calibration series or
  - Option B: delivering the satellite cross-calibration series then transitioning to a multimission hyperspectral smallsat series following launches three and four.

- Both options would **launch two satellites every two years**, subject to ongoing funding.

- UNSW Canberra Space assesses the SCR mission is ready for phase B mission development analysis following selection of the preferred option and completion of all open points and questions described at the end of the study. This report will inform the Australian Space Agency's Earth Observation Technical Roadmap.

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5 Executive summary

Australia is currently one of the largest users of satellite Earth Observation (EO) data worldwide, with these data coming from foreign governments and the private sector. Our access to these data is negotiated through partnership agreements, with Australia working to support the objectives of our partners and help them achieve efficiencies in their programmes. Australia's continued access, or 'securing data supply', under these partnerships are assessed as being at moderate to high risk, and require urgent attention.[1]

The 2016 Australian Earth Observation Community Plan 2026 highlights the need for Australia to be an essential component of the international EO capability, delivering benefits to the international community and securing our access to and involvement in international EO programmes.

The **Australian Satellite Cross-Calibration Radiometer (SCR) series** aims to directly improve the calibration of the smaller optical satellites increasingly used in the commercial Earth observation sector to deliver more interoperable data. These data quality improvements are achieved through cross-calibration – quantification of the differences in data signals received at the top of the atmosphere – of different Earth observation satellites. In effect, this means that data from one satellite can be combined with data from other satellites to increase their overall utility. Also, increases in the radiometric accuracy of optical satellite Earth Observation Analysis Ready Data from 3% to 1% are expected and this translates to the ability of identifying a specific crop where before it was only possible to identify generic agricultural activity.

SCR would secure Australian data supply by

- contributing to the global observing system,
- strengthening relationships with other space fairing nations, and
- contributing to the goals set out in the Australian Civil Space Strategy 2019-2028[2].

SCR also provides an opportunity for the Australian space sector including manufacturing, mission operations, partnering and mentoring through working with an established space program.

This study was conducted by UNSW Canberra Space with support from Geoscience Australia (GA), the Australian Space Agency (The Agency) and Commonwealth Scientific and Industrial Research Organisation (CSIRO). It applied a concurrent engineering methodology aiming for objectives aligned to the NASA systems engineering approach (Defined in section 6) to derive a space mission feasibility assessment and programmatic cost estimation. The core study team comprised 11 experts from across the engineering and space sectors plus additional support. In total, the study involved 40 experts from 13 organisations worldwide.

SCR satellites would be launched into orbits where they would provide coincident imagery opportunities with several **highly calibrated Earth Observation missions** such as the NASA/USGS (United States Geological Survey) Landsat, EC (European Commission) Sentinel or Planet's SuperDove series. By performing coincident, hyperspectral observations, they provide highly accurate and stable cross-calibration data to targeted cooperative missions with lower radiometric accuracy.

The **SCR series would launch 2 satellites every 2 years starting with a pair of pathfinder missions** in Q4 2023 followed by the full operational capability (FOC) as of Q4 2025 (cf. Figure 1).

[1] Australian Earth Observation Community Coordinating Group (2016), Australian Earth Observation Community Plan 2026: Delivering essential information and services for Australia's future, p. 13.
[2] Australian Space Agency (2019), Advancing Space: Australian Civil Space Strategy 2019-2028, https://publications.industry.gov.au/publications/advancing-space-australian-civil-space-strategy-2019-2028.pdf, accessed 14/01/2021

Following FOC, two options were identified:

- Option A delivers the satellite cross-calibration series.
- Option B delivers the satellite cross-calibration series then transitions to a multimission hyperspectral smallsat series incorporating requirements from CSIRO and SmartSat CRC's Aquawatch mission[3] in addition to ANU's OzFuel mission[4] following launches three and four towards the end of the decade.

The pathfinder missions, while technically aligned, pursue complimentary purposes:

- **SCR 1 is a low-risk version** relying on COTS systems to facilitate a launch at the same time as NASA's CLARREO-Pathfinder mission in Q4 2023.
- **SCR 2 is the opportunity for AUS industry** to ramp up its manufacturing capability and provide significant Australian content.

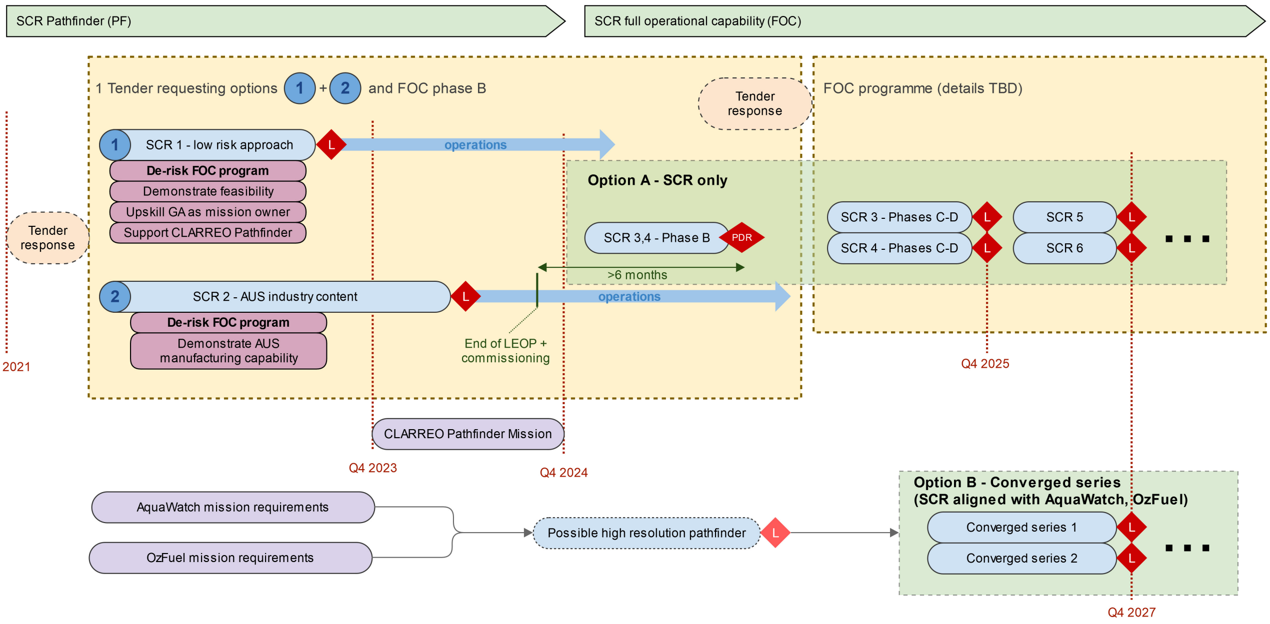

Figure 1: SCR programme overview (for detailed description refer to section 9.3)

During the study, mission observation requirements were derived to meet the needs of the user community working with SCR data and deliver a technical concept that is feasible for the current and expected Australian space manufacturing capability. For most parameters, these requirements align with those publicly presented by USGS in 2019[5].

The **primary instrument** to achieve those observation requirements would be a **hyperspectral, imaging spectrometer**. While this is not new technology, the primary technical challenge is to achieve the precise radiometric accuracy required for the mission concept. Consequently, it is expected that **instrument calibration could be a key area of collaboration with potential partners like USGS or NASA** calibration facilities and experts.

The large amounts of data generated by SCR means a network of ground stations is needed, presenting a second area of international collaboration.

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[3] https://smartsatcrc.com/projects/next-generation-earth-observation-data-services/phase-0-aquawatch-australia/

[4] https://inspace.anu.edu.au/ozfuel#

[5] *Christopherson, J., JACIE 2019,* https://calval.cr.usgs.gov/apps/sites/default/files/jacie/Christopherson-Need-for-an-On-Orbit-Gold-Standard.pdf

Four technological elements have been identified as opportunities for immediate de-risking and local manufacturing capability increase:

- A **hyperspectral instrument** meeting the SCR observation and size requirements
- An **on-board calibration subsystem** for hyperspectral small satellites
- A **payload data handling subsystem** capable of handling data rates of at least 200Mbps and of simultaneously writing to and reading from mass memory
- An **X-band antenna and radio** for small satellites capable of transferring data with at least 250Mbps to existing ground stations

In addition, a number of open technical questions have been identified that require further assessment in future design phases. (see section 12.1 for details)

The mission cost has been derived using two independent methodologies. A bottom-up costing approach estimated ROM costs for each mission element and summed them to obtain a **total contracted cost of AUD36M including design, build, launch and flying a single SCR mission** (see section 10.1 for details). The bottom-up costing was informed by a desktop study of recent satellites and a focused Request for Information (RFI) activity (see section 11.6.3.1 and 11.6.3.2 respectively for details). In parallel, a parametric satellite mission cost model has been applied and supports the above cost figure. This model has been calibrated to the Australian space context by comparing its results to actual costs of two recent Australian satellite missions.

The **mission owner would be the Australian government and it would be responsible for project management, tender evaluation, contract management, ground station operations, ground calibration, facilitating data utilisation and engagement activities**.

- The large data volumes being downloaded from SCR would require a network of ground stations. This ground station network could comprise combinations of existing Australian and partner government stations, commercial stations and new build stations at new sites.
- As SCR's primary mission is calibration, ground calibration requirements are considerably higher than a traditional mission and may use many existing sites and new sites.
- The mission owner would also facilitate data utilisation activities including data processing from Level 0 to Level 3 products, high availability global data distribution and data archiving.
- Engagement activities such as with Australian space education facilities.

A key schedule driver is parallel operation of SCR 1 with the NASA CLARREO-Pathfinder mission, currently expected in Q4 2023, if possible. Assuming 18 months is used to develop mission and 3 months is used for on-orbit commissioning, procurement would need to begin in late 2021. However, if this alignment is not possible, all SCR elements remain useful and desirable for the reasons outlined.

A risk assessment has identified key programme risks and applicable mitigation strategies. The most critical risks can be mitigated through the establishment of international best-practice systems engineering and procurement processes by the mission owner. For these reasons, while the SCR mission could be done by Australia alone, partnership with an experienced space agency would be highly desirable.

If the mission proceeds to further design cycles, UNSW Canberra Space provides a pathway to phase B space mission analysis.

The results of **this study will inform the Australian Space Agency Earth Observation Technology Roadmap** ("the Roadmap") being developed by The Agency, in close partnership with the Bureau of Meteorology, CSIRO, the Department of Defence, Geoscience Australia and the Australian Earth observation community. .

6 Study context

To examine the technical feasibility of the SCR mission, this study has adopted the mission concept and preliminary requirements developed by USGS and NASA.

The study is consistent with the NASA definition of a phase A design study but it does not cover all of those elements; the missing elements are described in Section 12.1 Open points and questions[6].

Table 1: NASA 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 NASA's 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

7 Acknowledgements

This study was undertaken by the following study participants:

A full list of study participants can be found in Appendix A (Section 14).

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

8 Background

Satellite Earth observations contribute over $5 billion to Australia's annual GDP[7] 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 who depend on such services include Geoscience Australia, CSIRO, Bureau of Meteorology, and various Defence agencies. The US' Landsat satellite mission series and the European Sentinel satellite mission series have been, and continue to be, Australia's most important sources of Earth observations for land applications like agriculture, disaster mapping and environmental monitoring.

In 2019, a report commissioned by the Australian Government[8] found that combined Earth and marine observing is currently worth $29 billion to Australia, and $543 billion to Asia-Pacific Economic Cooperation (APEC) economies each year. The value to Australia is forecast to increase to $66.5 billion USD (approx. $A96 billion) by 2030. Having no Earth observing satellites of its own, Australia relies on partnerships with international satellite operators and space agencies to meet its Earth observation needs. Partners such as the United States Geological Survey (USGS), National Aeronautics and Space Administration (NASA) and European Commission (EC) operate satellites providing essential data to sectors representing approximately 75% of global GDP[9].

These global partnerships are built on a foundation of bi- and multi-lateral agreements, and a long-standing practice of collaboration in key 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 the full economic and scientific value of satellite data; calibration and validation are particularly vital as they ensure Australian governments and industry derive information from satellite data that is accurate and dependable.

In response to an approach in early 2019 from USGS and NASA to Geoscience Australia, as to whether Australia could potentially make a technological contribution to the US' Sustainable Land Imaging program (which includes the Landsat satellite missions), GA contracted UNSW Canberra Space to write a report on the viability of domestic (Australian) contributions to international missions, specifically the US Sustainable Land Imaging program. The commissioning of this study follows long standing discussions between GA and the USGS around increasing our partnership with a space-based contribution[10], provided to the US by GA, concluded that Australia is positioned to contribute technology that stems from the global paradigm shift towards developing miniaturised dis-aggregated space systems with on-board processing. These types of technology being actively developed and demonstrated by key players in Australia today – to augment and add considerable value to the Landsat mission without contributing significant risk.

In 2019, USGS proposed the benefits of an SCR mission which both Australia and its US collaborators recognised as beneficial to the global remote sensing community given the proliferation of Earth observation missions. Without an improved means of inter-calibration, much of the benefit from these observations are difficult to extract. In late 2020, the US released a Requests for Information about potential contributes to the LandsatNext program. In addition to press releases from NASA/USGS contractors, the SCR series and the desire to launch the series

[7] 2015. The Value of Earth Observations from Space to Australia. ACIL Allen Consulting Pty. Ltd.
[8] 2020. Current and future value of earth and marine observing to the Asia-Pacific region. Nous Group for the Australian Government.
[9] 2016. The Economic Impact of Geospatial Services. Alpha Beta Strategy & Economics.
[10] 2019. A possible Australian technical contribution to augment the US Sustainable Land Imaging program.

to align with CLAREO-Pathfinder in late 2023 was established. Australia judged the Satellite Cross-Calibration Radiometer (SCR) series as the area in which the most valuable contribution to partner land imaging programs could be made. Accordingly, GA asked UNSW Canberra Space to perform, with representatives from the Australian government Earth observations community, a technical / budget / schedule feasibility study for possible missions that would meet the requirements of such an SCR series, while being within the grasp of the Australian space sector and contributing to the growth of Australian space industry, Australian advanced manufacturing capabilities, and the future highly skilled Australian workforce.

The context for such a study at UNSW Canberra Space is the Australian National Concurrent Design Facility (ANCDF), which was established by UNSW Canberra 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 rapid yet accurate immersive design and feasibility studies can be performed, with the space engineers and the customer/user sitting together for the purpose, to develop and test the viability of proposed missions to meet customer needs. In recent years, studies in the facility have included the NICSAT study for and with the National Intelligence Community, the Aquawatch study for and with CSIRO, and the Lamanon intelligent-Earth-observing satellite study with CNES and Airbus. 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.

9 Mission overview and background

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.

9.1 Mission concept

The high-level mission objective is as follows:

> The SCR mission programme would collect coincident spectral radiometer data between cooperative optical satellite missions for the purpose of enabling cross-calibration in a continuous, worldwide service.

Each of the SCR satellites in the programme would be a small satellite (<100kg) operating a hyperspectral sensor in a low Earth orbit (LEO). The orbit would be selected to enable coincident observation with both highly-calibrated optical missions (e.g. Landsat 8, Sentinel 2) and targeted cooperative missions (e.g. Planet Doves). It would thus be possible to transfer the radiometric response of the highly-calibrated reference mission to the target instrument. As a consequence, the interoperability between the two observing systems is improved.

The mission architecture is depicted schematically in Figure 2. The system of interest consists of the SCR spacecraft, a network of ground stations and station-specific archives, a stitcher combining data from different ground stations into the mission archive and a L0 processor. As such, there are three main interfaces to related elements: Higher level data products are created by Geoscience Australia from the L0 data. The reference missions determine orbit and station keeping needs for the SCR mission, and its payload is tasked based on opportunities for coincident observations with the target missions.

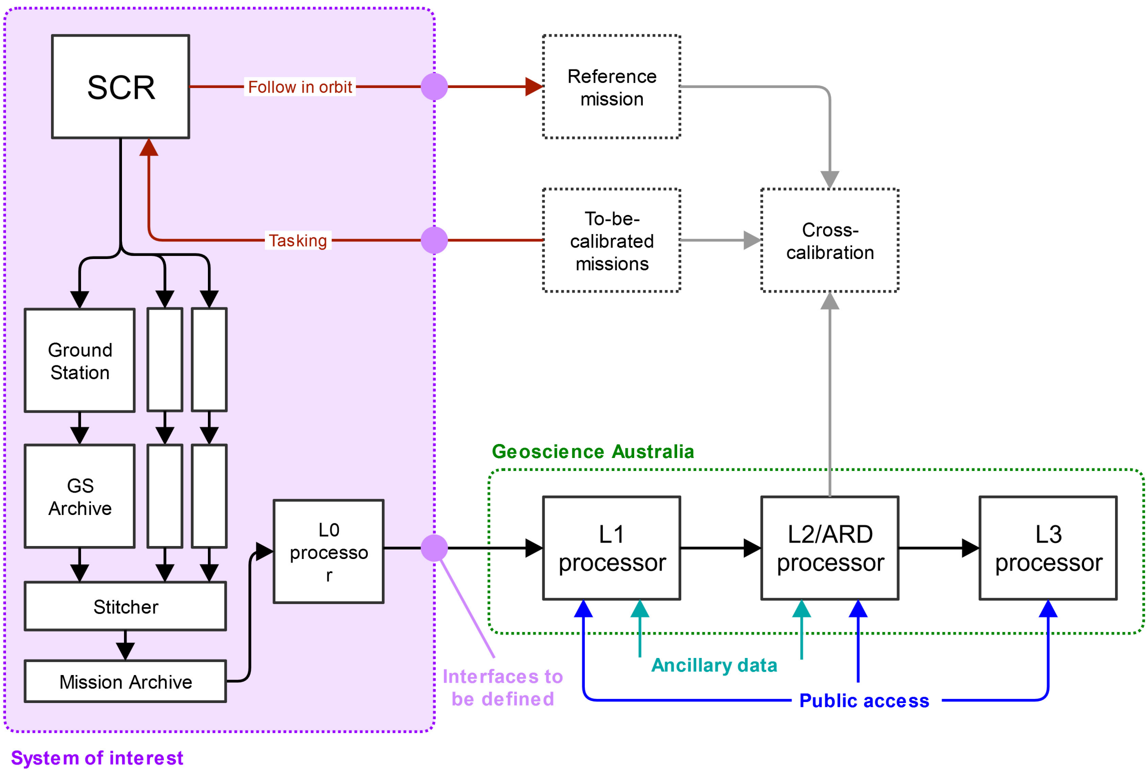

Figure 2: SCR mission architecture overview

9.2 Benefits

The SCR mission would provide both scientific, policy and industry benefits. They are outlined in the following sections.

9.2.1 Scientific benefits

The US Academy of Science 2018 Decadal Survey for Earth Science (as well as the 2007 Decadal Survey) recommended the development of a space-borne radiometer to acquire high-accuracy spectral/spatial imagery of the Earth's surface to provide reference calibrations for other Earth observation sensors.

In fact, the Survey listed the establishment of reference radiance inter-calibration as one of its most important targeted observables. Such a reference radiometer would aid in enhancing the inter-operability of historic and future sensor datasets (e.g. Landsat) and providing improvements in the accuracy and reliability of climate science models.

In general, by moving the radiometric accuracy of optical analysis-ready data from a radiometric accuracy of 3% to 1% it would be possible to move the world's most common Earth observation data type (optical imagery) from applications like identifying agricultural activity through to identifying the specific crop. The SCR mission would enable this for the targeted cooperative missions. Related to agriculture, climate change is potentially a major beneficiary of cross-calibration transfer to support climate data records and fusion for apps in support of climate adaptation.

9.2.2 Policy benefits

The core benefit of the SCR mission would be to secure Australia's data supply[11] because it will support the development of multi-mission space applications that provide EO data users with a degree of protection against international policy changes or technical failures. In addition, the programme would also provide a means to strengthen Australia's relationship with the US and other partners, helping bolster the case for ongoing access to their data.

SCR would provide a coherent end to the narrative of Australia relying entirely on international satellite data in a way that is consistent with the Australian narrative with the Committee on Earth Observation Satellites (CEOS) and Group on Earth Observations (GEO) of improving utilisation of global EO data, partnering and making a unique contribution.

The continuous launch nature of this mission would support the scaling of capabilities including manufacturing in the Australian space sector. It thus extends Australia's sovereign capabilities from space utilisation into space hardware. In doing so, it would build Australian space heritage and increase the Technology Readiness Levels (TRL) of the Australian space sector. The result would be an increase of skills in Australia across the supply chain and within all related sectors.

The SCR mission programme would also create potential opportunities to formally partner on mission development with established space agency partners. This, in turn, provides a pathway for local stakeholders to access mentorship and support that helps develop their capability and bolster international profile.

9.2.3 Industry benefits

Accuracy and dependability are critical to ensuring satellite data is trusted by Australian government and industry. The 2020 report, *Harvesting the Benefits of Earth Observation*[12] (FrontierSI for the Australian Government) found a lack of trust in satellite data was a key factor in its relatively low adoption rates in the Australian agricultural sector. Addressing trust issues will help close the gap

[11] University of Queensland, *Australia's access to Earth observation satellites is high risk*, https://www.spatialsource.com.au/remote-sensing/earth-observation-satellites-risk, accessed on 01/03/2021

[12] Frontier SI, *Harvesting the Benefits of Earth Observation*, https://www.frontiersi.com.au/wp-content/uploads/2020/08/FrontierSI_DigitalEarth_BenefitsEarthObservation.pdf accessed on 09/02/2021

between potential and actual use of Earth observation in this sector which operates over more than half of Australia's landmass and contributes ~2.2% of our GDP.

Data accuracy is also a major concern in the rapidly developing commercial smallsat sector. Internationally, there has been an explosion in the number of satellites launched and slated for launch over the coming years – driven entirely by the smallsat (500kg or less) and mega-constellations of the Space 2.0 movement. These small, low-cost platforms tend to lack on board calibration, and therefore space-based calibration transfer or vicarious calibration using ground sites are critical.

9.3 Timeline

The development of the implementation timeline is based on a desire for SCR to operate in parallel with the CLARREO-Pathfinder mission (outlined below at section 9.5.2), expected to be launched in Q4 2023 with an operational life of 1 year.

In addition, the earliest possible operation of the SCR mission would enable coincident observations between instruments on the current series of Landsat satellites (Landsat 8 and soon Landsat 9) and a previous generation of the Landsat series (Landsat 7 and earlier). Landsat 7, the last of the previous generation of Landsat satellites is already operating beyond its originally planned End of Life.

To achieve this desired timeline, an 18 month build and 3 month commissioning schedule indicate that a decision to proceed would be required in late 2021.

Critical elements identified during the mission risk assessment (see section 11.1.3) as driving the schedule include:

- Establishing suitable arrangements for full flow of technical and other information between an Australian team and any foreign space agency teams working on similar concepts
- A few key technology de-risking activities (see section 11.6.4)
- A preliminary design activity of the space and ground segments of the mission (Phase B study)
- The time required for tender and procurement of the SCR missions once the previous activities are completed.

The proposed overall schedule is included in the schematic mission implementation plan in Figure 1).

To achieve the competing goals of achieving this challenging timeline and increasing the Australian industry content in the mission, a two-way pathfinder mission concept is proposed. A low-risk pathfinder mission would utilise COTS elements as far as possible to ensure a launch within the required timeline, while an Australian industry-focussed mission would be developed in parallel with a stronger emphasis on the Australian components than on meeting the Q4 2023 launch date.

The ensuing SCR missions would be launched in pairs every two years, i.e. SCR 3 and SCR 4 in 2025, SCR 5 and SCR 6 in 2027 and so on.

9.4 Orbit

The SCR spacecraft would be launched into low Earth orbits (LEO). There are two generic options how the mission orbits can be defined depending on the selected operational concept:

1. **An optimised orbit maximising coincident observation opportunities with a selected group of reference and target missions**. This strategy would provide complete flexibility of defining the orbital parameters to enable coincident observations with as many of the target and reference missions as possible. Identifying such an orbit is a moderately complex task and is proposed as a precursor activity to any further mission design steps. In this scenario, the SCR mission would enable cross calibration between an arbitrary combination of other missions.
2. **An orbit of same altitude, inclination and RAAN as one reference mission and phased to trail that mission within a predefined time window**. Under this strategy the orbit is defined by the reference mission that is being followed and no detailed analysis is required. For the Landsat and Sentinel 2 satellites the orbits would be sun-synchronous in altitudes of about 700km and 800km respectively. In this scenario, the cross-calibration would be mainly limited to the followed reference mission and any other mission that happens to achieve coincident observations.

The proposed study into the selection of a suitable orbit should also compare the above two generic options in terms of potential of their operational and scientific value.

Especially the second strategy would require station keeping capability in the form of on-board propulsion to maintain the satellite within the required relative position to the target satellite. Propulsion requirements on scenario 1 are less demanding. Under certain conditions a no-propulsion option may even be conceivable for the first scenario.

Further details into the orbit selection and propulsion options are provided in section 11.2.4.

9.5 Related missions

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

9.5.1 LandsatNext

Landsat 7 and 8 are currently operational and provide Earth observation image products for use by Australia for disaster response, land use monitoring, agriculture, resource exploration, and water security[13]. Landsat 9 is identical to Landsat 8, and is scheduled for launch in September 2021 to replace Landsat 7, which is nearing the end of its life[14]. Landsat 10 will provide an increase in the spectral bands provided by Landsat 8 and 9, including the Sentinel 2 bands, and additional bands for a total of 20 visible and near-infrared (VNIR)/short-wave infrared (SWIR) bands and 5 thermal infrared (TIR) bands[15]. The LandsatNext programme is expected to have multiple components, including a traditional imaging satellite or constellation, and companion satellites for calibration and experimentation[16,17].

9.5.2 NASA's CLARREO Pathfinder

The Climate Absolute Radiance and Refractivity Observatory (CLARREO) Pathfinder Project is a NASA mission to launch a reflected solar spectrometer that will measure reflected solar radiation from Earth with an accuracy 5-10 times better than existing space-based sensors. This high accuracy allows changes in the Earth's climate to be detected much earlier than current sensors permit, which will help us understand how quickly the climate is changing and allow policymakers to respond more effectively[18].

CLARREO Pathfinder began development in 2016 and is expected to operate from the International Space Station (ISS) from Q4 2023. The spectrometer will also be used to demonstrate calibration of sensors on other Earth-observation satellites that cross paths with CLARREO Pathfinder[19]. However, the orbital dynamics of the ISS limit the number of Earth observing satellites and global regions that this calibration can service.

9.5.3 UK NPL's TRUTHS

The TRUTHS mission is a climate and calibration observing system designed to improve confidence in climate-change forecasts. TRUTHS stands for Traceable Radiometry Underpinning Terrestrial- and Helio- Studies, and will carry a hyperspectral imager to measure incoming solar radiation and outgoing reflected radiation with high accuracy achieved through an on-board calibration system conceived by the UK's National Physical Laboratory (NPL). This mission is expected to enable a 10-fold improvement in accuracy of Earth Observation data, halving the time required for climate scientists to determine changes in the Earth's temperature with high confidence[20]. The data from TRUTHS will also be used to cross-calibrate the sensors of other satellites[21], in a similar manner to NASA's CLARREO Pathfinder. The separate missions are complementary, with the two missions

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[13] Geoscience Australia, 40 Years of Landsat in Australia, http://www.ga.gov.au/news-events/features/40-years-of-landsat-in-australia, accessed 27 Jan 2021.
[14] USGS, Landsat 9, https://www.usgs.gov/core-science-systems/nli/landsat/landsat-9?qt-science_support_page_related_con=0#qt-science_support_page_related_con, accessed 27 Jan 2021.
[15] Newman, T., 2020, USGS Update on Landsat Next, https://www.fgdc.gov/ngac/meetings/december-2020/usgs-landsat-program-update-ngac-dec-2020.pdf.
[16] Christopherson, J., 2019, An SLI Cross-Calibration Radiometer (SCR) Concept for Improved Calibration of Disaggregated Earth Observing Satellites Systems, https://calval.cr.usgs.gov/apps/sites/default/files/jacie/Christopherson-Need-for-an-On-Orbit-Gold-Standard.pdf.
[17] Ball Aerospace, 2020, Ball Aerospace Selected by NASA for Three Studies to Develop Future Sustainable Land Imaging Technologies, https://www.ball.com/aerospace/newsroom/detail?newsid=124038.
[18] NASA, CLARREO Pathfinder, https://clarreo-pathfinder.larc.nasa.gov/, accessed 27 Jan 2021.
[19] NASA, 2016, CLARREO Pathfinder Undergoes Successful Mission Concept Review, https://www.nasa.gov/feature/langley/clarreo-pathfinder-undergoes-successful-mission-concept-review.
[20] ESA, 2019, THRUTHS: A New Potential ESA Earth Watch Mission, https://www.esa.int/Applications/Observing_the_Earth/TRUTHS_a_new_potential_ESA_Earth_Watch_mission.
[21] Airbus, 2020, Airbus Wins European Space Agency TRUTHS Mission Study for Metrological Traceability of Earth Observation Data, https://www.airbus.com/newsroom/press-releases/en/2020/11/airbus-wins-european-space-agency-truths-mission-study-for-metrological-traceability-of-earth-observation-data.html.

targeting sensors with different spatial resolutions and, TRUTHS measuring incoming solar radiation in addition to reflected radiation. Overlapping flights of the two missions, and any future missions, provide greater temporal coverage and opportunity to calibrate more sensors. Comparing data from the different missions also allows their uncertainties to be validated[22]. TRUTHS is being led by the UK Space Agency as part of the European Space Agency's (ESA's) Earth Watch programme[23]. The system feasibility and predevelopment phase of the mission is currently being undertaken by Airbus UK[24], with launch targeted for 2026[25].

9.5.4 CSIRO and SmartSat CRC's AquaWatch Australia

AquaWatch Australia is a program to monitor inland and coastal water quality from ground and from space combining sensor data to create information products for the benefit of various downstream users. A second goal of the program is to grow Australia's space industry[26]. The programme is currently in phase 0 implemented by CSIRO and the SmartSat CRC together with a range of government and industry partners[27]. The main purpose of this phase is to identify user needs and identify technical and programmatic feasibility of the whole program. It is likely that AquaWatch, just as SCR, will rely on a space-based hyperspectral instrument.

9.5.5 ANU's OzFuel mission

The ANU and Optus have joined to create a Bushfire Research Centre of Excellence pursuing various short, medium and long-term objectives to help detect bushfires and extinguish them shortly after ignition[28]. Part of this programme is a cubesat mission named OzFuel. It will host infrared sensors to measure forest fuel load and vegetation moisture levels.[29] If deployed in a LEO constellation, OzFuel would enable near-real time analysis of fuel conditions supporting bushfires.

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[22] Fox, N. and Green, P., 2020, Traceable Radiometry Underpinning Terrestrial- and Helio-Studies (TRUTHS): An Element of a Space-Based Climate and Calibration Observatory, *Remote Sensing*, 12(15), 2400, https://doi.org/10.3390/rs12152400.
[23] NPL, Improving Earth Observation Data to Drive Improved Climate Change Modelling, https://www.npl.co.uk/earth-observation/truths, accessed 27 Jan 2021.
[24] Kuper, S., 2020, Airbus Wins ESA TRUTHS Mission Study for Metrological Traceability of Earth Observation Data, *Space Connect*, https://www.spaceconnectonline.com.au/operations/4612-airbus-wins-esa-truths-mission-study-for-metrological-traceability-of-earth-observation-data.
[25] Amos, J, 2020, Space Mission to Reveal 'Truths' About Climate Change, https://www.bbc.com/news/science-environment-51197453.
[26] SmartSat CRC, not dated, AquaWatch Australia, https://smartsatcrc.com/app/uploads/SmartSat_FactSheet_AquaWatch-FINAL.pdf, accessed 12/02/2021
[27] 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
[28] 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 accessed on 12/02/2021
[29] ANU, not dated, ANU-Optus Bushfire Research Centre of Excellence – Building a national defence system against catastrophic bushfires, https://www.anu.edu.au/files/resource/DVC200149%20ANU-Optus%20BRC%20brochure%20v6%20%28150ppi%29.pdf accessed on 12/02/2021

9.5.6 Australia as a global test track for Earth observation calibration and validation

Building on Australia's global reputation in satellite Earth observation calibration and validation there are active discussions across Australia about a proposal to codify this position and developing Australia as the global satellite test track for Earth observation satellite 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 Satellite Cross-Calibration Radiometers to provide improved accuracy and consistency between optical satellites (this study)

9.6 Relationship between SCR and related missions

The CLARREO mission was recommended in the 2007 Decadal Survey to deliver needed climate model and sensor inter-calibration improvements. Although CLARREO was discontinued the CLARREO Pathfinder (PF) mission was begun in 2016 to raise the TRL for the radiometer subsystems to demonstrate the SI-traceable accuracies needed for improved intercalibration of multiple image sensors. CLARREO PF is slated for installation on the ISS in 2023. The HySICS spectrometer on CLARREO PF will use the sun and moon as calibration sources with a baseline objective of 0.3% (1 sigma) reflectance calibration uncertainty for the contiguous spectrum from 350nm to 2300nm, covering over 95% of the Earth's reflected solar spectrum.[30]

When CLARREO PF and TRUTHS are operational they will serve as a primary calibration layer with unparalleled determination of TOA spectral radiance. The SCRs would serve as a transfer layer and provide accurate and stable measurements of TOA radiance for cross-calibration of other EO imaging sensors

The SCR would provide another foundational system to achieve the higher accuracy and stable observations needed to reduce the radiometric uncertainties in optical sensor image data products. Specifically, the SCR would be a hyperspectral imaging spectrometer providing improved spatial resolution compared to CLARREO PF (from ~150 m to <100 m) and a radiometric uncertainty of 1% which can be transferred to other Earth observation platforms.

[30] NASA, CLARREO Pathfinder, https://clarreo-pathfinder.larc.nasa.gov/, accessed 27 Jan 2021.

10 Mission elements

This chapter provides a high-level overview of all mission elements (see section 9.1) and compares differences in procurement options to come to an estimate of ROM cost for each of them. This information is then used to establish a bottom-up ROM cost estimate for an SCR mission. The description of each element is kept brief here. Further explaining details are provided in referenced section within chapter 11.

10.1 Overview

The mission elements are listed in Table 2 together with an estimate of the rough order of magnitude (ROM) cost for the aspects of the SCR mission that would need to be procured. Note that the table lists costs for a single SCR mission. At this stage, it is a valid assumption that this cost is valid for both the pathfinder missions as well as the first full operational SCR missions. Initial non-recurrent developments needed for the pathfinder would be compensated by the larger technical demands on the FOC missions in a first order approximation. For later missions, scale effects could be leveraged depending on the procurement details.

Specific known uncertainties are covered by a local margin. For all other elements that show a margin of 0%, the uncertainty is covered through the 20% margin applied at the highest level.

The margins apply to the line in which they are listed. This means that the *Cost without any margin* column always lists each element's cost as derived if not considering any lower-level margins. The *ROM cost* column on the other hand applies the listed margin to the sum of the lower level *ROM cost* (including the lower level margin). For example, *SCR mission* ROM cost of AUD36.0 M is computed as the sum of the next lower level ROM costs (0.4 + 4.0 + 4.1 + 1.6 + 20.0) = AUD30.0 M plus 20% margin.

Table 2: ROM cost estimate for a single SCR mission

Component	Cost without any margin	Margin (locally applied)	ROM cost
SCR Mission	**AUD25.2 M**	**20%**	**AUD36.0 M**
Ground Segment	AUD0.4 M	0%	AUD0.4 M
Launcher	AUD3.6 M	10%	AUD4.0 M
Mission Operations Centre	AUD4.1 M	0%	AUD4.1 M
Processing pipeline	AUD1.6 M	0%	AUD1.6 M
SCR Satellite	AUD15.5 M	0%	AUD20.0 M
Environmental Qualification	AUD0.2 M	20%	AUD0.2 M
Integration + System-level Tests	AUD1.5 M	20%	AUD1.8 M
Payload	AUD1.8 M	30%	AUD2.4 M
Payload Calibration	AUD1.5 M	100%	AUD3.0 M
Platform / Bus	AUD10.5 M	0%	AUD12.6 M

In parallel to the bottom-up cost estimation approach described above, the CoBRA parametric cost model[31] has been utilized to provide a sanity check of the mission cost. Details of the model are provided in section 11.6.5. This approach yields a total mission cost of AUD83 M (FY2020) when adjusted for inflation and currency conversion with an error of ±25%. Due to the underlying cost data making up this model, its transferability to the modern Australian satellite manufacturing context is questionable. In a calibration exercise, the model's cost estimate has been translated to the Australian context resulting in an adjusted cost of between AUD17 M to AUD33 M. This excellently confirms the bottom-up figures derived here. Section 11.6.5.1 provides further details on the limitations and calibration of the CoBRA cost model.

Considering these findings leads to the conclusion that the estimated ROM mission cost provides a credible assessment of the actual SCR mission cost at this early stage of design. It is recommended to perform a refinement of this cost assessment as part of the next step in the mission development process once the technical concept is properly defined.

The following sections provide for each of the mission elements listed in the bottom-up cost estimation:

- A concise description of what is included in each element
- A brief discussion on different procurement options (i.e. make vs. buy considerations). These are kept generic, ignoring any specific vendors or manufacturers
- An assessment of specific implementation options, listing potential vendors
- An estimate of the element's ROM cost and uncertainty if available

[31] Yoshida, J. & Cowdin, M. & Mize, T. & Kellogg, R. & Bearden, D.. (2013). Complexity analysis of the cost effectiveness of PI-led NASA science missions. IEEE Aerospace Conference Proceedings. 1-14. 10.1109/AERO.2013.6496935.

10.2 Payload

10.2.1 Description

The SCR is envisioned to be a hyperspectral imaging spectrometer that provides the performance capability needed to meet the mission requirements which were refined in the study.

The SCR instrument would include a telescope and focal plane arrays to cover a spectral range from 400-2400 nm with a 10 nm band centre wavelength spacing. The instrument would provide SNR between 100 – 300 depending on the spectral band ranges. In addition, the SCR platform would include a means to accurately maintain radiometric calibration over the mission life. This could include a passive solar calibration unit or an LED based calibrator.

10.2.2 Procurement approach aspects

Several options were considered for a SCR Pathfinder (PF) and SCR Full Operational Capacity mission (FOC). A review of the currently available instruments and the descriptions of instruments being designed for use as the SCR was conducted. The SCR mission requirement for radiometric accuracy places demanding instrument requirements on both the optical and detector subsystems.

An off the shelf instrument is currently unavailable and to fulfil the SCR FOC mission a bespoke hyperspectral imaging spectrometer would be required to meet all the SCR mission requirements.

10.2.3 Implementation options

Several options were considered for a SCR PF and SCR FOC mission. A review of the currently available off the shelf instruments and those being designed for use to support the Sustainable Land Imaging program was conducted. Details of these options are discussed in section 11.3.3. Potential manufacturers include Ball Aerospace, Cosine NL, Headwall Photonics or an Australian entity.

10.2.4 Element cost estimate

Based on previous experience and expert opinion in combination with confidential quotes for commercial instrument options, the cost for the payload including development, build and space qualification testing is expected to be AUD1.8 M with a relatively large uncertainty of 30%.

10.3 Spacecraft bus

10.3.1 Description

The spacecraft bus houses all the necessary systems required to accommodate and support the payload for both the launch and in-orbit operational phases of the mission.

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 50 kg and measuring approximately 50 x 50 x 50 cm (payload included) – would be most appropriate given the expected payload weight and dimensions.

10.3.2 Procurement approach aspects

To procure microsat buses, two options are available:

- Procure an off-the-shelf microsat bus from a satellite provider.
- Contract the development of a custom microsat bus from a satellite developer/integrator.

Note that all identified off-the-shelf microsat systems are from overseas suppliers (see section 11.6.3) and therefore these spacecraft, or components of these spacecraft, maybe subject to export control.

10.3.3 Implementation options

For off-the-shelf microsat buses, the following options were identified as being suitable for the GA SCR mission and are available:

Table 3: Overview of suitable micro-satellite platforms

Supplier	Country	Microsat Bus	Comments
Ball Aerospace & Technology Group	USA	BCP-100	Datasheet[32]
Berlin Space Technology	Germany	LEOS-50	Datasheet[33]
Momentus	USA	Vigoride	Datasheet[34]
Raytheon (previously Blue Canyon Technologies Inc.)	USA	X-Sat	Datasheet[35]
RocketLabUSA	USA	Photon	Datasheet[36] Includes launch[37]
Satellogic	Argentina		
SSTL	UK	SSTL-Micro	Datasheet[38]
York Space Systems	USA	S-CLASS	Datasheet[39]

For contracting the development of a custom satellite bus with an Australian organisation, the following Australian organisations have been identified as having sufficient skills and experience to grow and develop microsat spacecraft systems: Inovor, SkyKraft, UNSW Canberra Space and potentially Sitael.

10.3.4 Element cost estimate

An Australian-made bus is expected to cost around AUD10.5 M as derived in detail in section 11.6.2. This number is reduced to between AUD4.3 M and AUD7.2 M when procuring a COTS bus.

[32] http://www.ball.com/aerospace/Aerospace/media/Aerospace/Downloads/D3072_BCP100-ds_1_14.pdf?ext=.pdf
[33] https://www.berlin-space-tech.com/wp-content/uploads/2020/07/PFR-PR28_LEOS-50__V1.00_.pdf
[34] https://momentus.docsend.com/view/xmuxgesufvqfqh8p
[35] https://www.bluecanyontech.com/spacecraft
[36] https://www.rocketlabusa.com/satellites/
[37] https://www.nasaspaceflight.com/2020/09/rocket-lab-debuts-photon/
[38] https://www.sstl.co.uk/getmedia/78c3ae88-0f17-40a1-9448-8c3c7e9f6944/SSTL-MICRO.pdf
[39] https://www.yorkspacesystems.com/s-class/

10.4 Integration and system-level testing

10.4.1 Description

Integration and system-level testing begins 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), along with the connection of 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 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 to this, 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 planning and execution of system level testing

10.4.2 Procurement approach aspects

Procurement of integration and system-level testing services would typically be performed by the spacecraft bus integrator, but a third party could be sourced.

10.4.3 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 organisation or by a third party who then performs testing.

10.4.4 Element cost estimate

Spacecraft integration and system level testing are expected to cost approximately AUD1.5 M. With a margin of 20%, the estimated cost is AUD1.8 M. This cost assumes that four months are required for spacecraft integration in a cleanroom facility, with FTE staffing of two engineers. Six months in a cleanroom facility are required for system level testing, with FTE staffing of six engineers.

10.5 Payload calibration

10.5.1 Description

The purpose of calibrating EO sensors is to ensure characteristics of a remote object are accurately and reliably estimated over time. EO sensors require calibration to quantify the sensor's response to known radiometric input and to characterize the interactions and dependencies between the sensor optical, mechanical, and electronic components. Systematic biases are thereby identified through calibration.

The radiometric performance requirements for SCR are by definition very demanding and would require exceptionally reliable and accurate calibration of the instrument both on-ground and in flight.

10.5.2 Procurement approach aspects

Due to the high cost and technical complexity of instrument calibration it does not make sense to build such a facility in Australia. Ideally a collaboration with international partners in this area would provide an additional opportunity to increase Australian expertise for future space missions.

10.5.3 Implementation options

The on-ground radiometric calibration of the SCR would take place in a facility which provides SI traceable sources and known radiance to better than 1% accuracy in terms of spectral value and uniformity. An example facility is the NASA Goddard Laser for Absolute Measurement of Radiance (GLAMR).

An on-board radiometric calibration approach would require at least an LED-based illumination subsystem that provides radiometrically accurate and spatially uniform illumination of the focal plane(s). A passive solar calibration subsystem might be deployed, as the sun is a well-known and stable source. However, this adds complexity to the instrument that may not be necessary. The SCR would also maintain calibration by imaging of selected pseudo invariant calibration sites (PICS) on the Earth (some of which are part of the instrumented RadCalNet network and provide a direct measurement of surface reflectance) and monthly imaging campaigns of the moon

In addition to radiometric calibration, the SCR detectors and the optical system would be aligned during AIT operations and assessed for image quality and calibrated to generate correction factors such that each pixel is in the desired position. In-flight geometric calibration would be performed by imaging designated terrestrial target areas as part of on-going calibration operations so that image quality, georeferencing and image-to-image registration capabilities can be monitored.

The calibration concept is further detailed in section 11.3.2.

10.5.4 Element cost estimate

Costing for this element assumes that a calibration facility is provided by an international partner and that only facility use, travel and personnel costs need to be paid for. The cost estimate for the payload calibration under these assumptions is AUD1.5 M with a very large uncertainty of 100%. This implies that a large fraction of this cost namely the facility access fee may be supplied in kind by an international partner.

10.6 Environmental qualification and launch

10.6.1 Description

Environmental qualification testing forms part of an overarching effort to provide total mission assurance, i.e. establish the highest level of confidence possible that the fully integrated system (spacecraft bus + payload) would operate correctly on-orbit resulting in a successful mission. The environmental qualification test program is intended to demonstrate that the as-built system would perform correctly when subjected to a range of environmental conditions (launch + on-orbit operations) more severe than expected during the mission to verify positive design margins. The environmental stress screening activities further serve to identify any workmanship defects that could jeopardise the success of the mission. Formal system qualification tests are conducted on a flight representative engineering model (EM) spacecraft, and the flight model (FM) spacecraft would be exposed to reduced acceptance level test requirements for flight acceptance by the launch service provider (LSP).

Detailed environmental qualification requirements depend on the specific mission requirements, the LSP and launch vehicle (LV) selected to deliver the system to orbit. The LSP would stipulate the environmental qualification test requirements which need to be satisfied so that the space system can be accepted for launch into orbit. Therefore, it is critical to baseline a 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 reducing the risk of unnecessary hardware failure. The requirements along with a detailed description of the test schedule shall 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 system that is flight-representative (or as close to 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 AIT process to provide confidence in the system's operation and compliance with the system requirements as outlined in section 11.1.1.

The relevant environmental qualification tests to 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**)

10.6.2 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 SCR mission with the exception of 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, class 100 cleanroom with 2to crane and optical tables, large thermal vacuum chamber, a vibration test facility, and mass properties measurement equipment for centre of mass (CoM) and moments of inertia (MoI, principle axes only). NSTF personnel have the relevant experience to perform spacecraft environmental qualification testing and have the necessary ESD and contamination control procedures in place. Other test houses may not be familiar with the particularly strict handling requirements of space system hardware. Significant additional costs may be incurred if additional equipment is required and stricter process requirements are requested.

International travel to access overseas test facilities bears significant risk of hardware damage during transport and would incur additional personnel travel cost as well as increased administrative burden with regards to export/import control licenses.

10.6.3 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 risk, cost and administrative burden of coordinating multiple stakeholders.

10.6.4 Element cost estimate

The cost for this element is estimated at AUD200k with a 20% uncertainty margin. The details of this estimate are provided in section 11.6.1.

10.7 Processing pipeline and data distribution

10.7.1 Description

The data processor pipeline consists of one data assembly phase ('stitching') plus four processing stages (L0, L1, L2, L3). The stitcher would be provided by GA and would interface the mission archive to the L1 processor. A further description can be found in section 11.5.3.

A focus on secure software development should be made to ensure the risk of any cyberattack is sufficiently mitigated. See section 10.9.1 for possible impacts and relevant documents.

10.7.2 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 there is a body of knowledge and experience that can be drawn from.

10.7.3 Implementation options

The implementation should generally adhere to or follow best-practice EO community standards for the L1, L2, and L3 data processors. Relevant standards may include ISO 19131[40], ISO 19112[41], ISO 19115[42], COG[43], STAC[44], and CARD4L[45].

Data outputs from each stage should be appropriately licensed to maximise uptake (and thus national benefit) of the generated products. This may be achieved by licensing the data products under an 'open' license, such as CC BY[46] (or a variant thereof). Restrictive licensing may lower the acceptance and usage of the data products by organisations and consumers, or act as a barrier to their usage.

Generally, L0 data processors are bespoke to the mission series and need to be developed to work with the unprocessed payload data received from the spacecraft. It is unlikely that an existing/COTS L0 data processor that meets the requirements of the mission (without further work) could be procured. The level of re-use is dependent on the data format similarity coming from the spacecraft. A general software consultancy/team would be suitable, however a group with space systems knowledge would be preferred.

10.7.4 Element cost estimate

Development of the L0 processor is expected to cost AUD1.6M. This figure is conservative due to the higher risk identified in section 10.7.2.

[40] https://www.iso.org/standard/71297.html
[41] https://www.iso.org/standard/70742.html
[42] https://www.iso.org/standard/53798.html
[43] https://www.cogeo.org/
[44] https://stacspec.org/
[45] https://ceos.org/ard/index.html#slide1
[46] https://creativecommons.org/licenses/by/4.0/

10.8 Mission Operations Centre

10.8.1 Description

A Mission Operations Centre (MOC) is required for the satellite operators to control the SCR series spacecraft, monitor their health, respond to anomalies, and make payload data available to mission stakeholders. The level of staffing and infrastructure required for the MOC depends on the complexity of the spacecraft, the level of autonomy built into the spacecraft and operations software, the risk tolerance for the mission, and the data volume to be handled. For example, it is possible to reduce staffing levels if certain anomalies are handled autonomously by the spacecraft, and/or anomalies can be detected by the operations software and an on-call operator automatically notified. A 'lights out' approach is recommended, similar to Planet's approach[47], where a certain level of ground segment and space segment automation reduces the person-hours required for operations, and removes the need for a dedicated operations centre with 24/7 staffing.

With this approach in mind, the MOC can be, but does not need to be, a centralised workspace that the operations teamwork from. A modern MOC implementation features a secure web-based approach to operations, that allows the operators to work from anywhere with an internet connection without being restricted to a dedicated control room.

10.8.2 Procurement approach aspects

The MOC would be procured as a customised item from an Australian or international provider. As the MOC is always a customised element of a mission there are no COTS options available.

10.8.3 Implementation options

The infrastructure required for the MOC is primarily software. This software could be developed from the ground up, or an existing local or overseas system could be adapted to meet the needs of the SCR series spacecraft. Examples of existing systems in Australia are those developed by UNSW Canberra Space for operation of the Buccaneer Risk Mitigation Mission, M1, M2 Pathfinder, and M2 missions, or the mission control centre that is currently under development by Saber Astronautics for the Australian Space Agency.

10.8.4 Element cost estimate

The MOC is estimated to cost AUD4.1 M, a breakdown of which is shown in Table 13 in section 11.2.2. The cost consists of the person time required for development, validation and verification, and ongoing support of the operations infrastructure described in section 10.8.1, as well as operator training, and mission operations planning and execution. The cost does not include operator involvement in system level testing, which is covered in section 11.2.2.

[47] Henely, S., Baldwin-Pulcini, B., and Smith, K., 2019, Turning Off the Lights: Automating SkySat Mission Operations, *33rd Annual AIAA/USU Conference on Small Satellites*, Utah, USA.

10.9 Ground stations

10.9.1 Description

The mission would utilise S-band for TT&C (uplink/downlink) and X-band for science data transfer (downlink only).

The preliminary payload link budget (section 11.3.4) indicates that the ground station network would need to consist of Tier 1 stations, with Tier 3 stations inadequate due to their low antenna gain. A Tier 1 station would typically support link bandwidths in the range 100-1000Mbit/s, utilising a ~9 metre parabolic antenna to provide sufficient gain[48]. Approximately 75 contact minutes per mission per day are required to meet the data budget required for the mission. Tier 1 and Tier 3 S-band ground stations can be used for TT&C as the required data rates are lower, allowing the TT&C link budget to be satisfied with Tier 3 stations. Using Tier 3 stations for TT&C reduces contention on Tier 1 stations.

A ground station interface would be required to allow the ground stations to be tasked by mission operators. The interface would bridge individual ground stations' tracking interfaces to the scheduling and tasking software used in the mission operations centre. GA should manage and operate the tasking interface within their network to reduce the surface area of publicly exposed interfaces. Cybersecurity risks should be considered and managed appropriately. Possible risks include a data breach, network/system compromise, and loss of access to the ground stations. The contractor should utilise appropriate processes, workflows, and standards to develop secure software. One starting point may be the Australian Government Information Security Manual[49] [50].

10.9.2 Procurement approach aspects

The ground station network is expected to be contributed by GA using existing assets. The development of the tasking interface is low-risk and could be procured internationally or locally with minimal difference. International procurement may increase the risk of a cybersecurity vulnerability and incur greater audit difficulty.

10.9.3 Implementation options

A ground station network could be provided in-kind by Geoscience Australia through Australian National Ground Segment Technical Team (ANGSTT), and by USGS through the Landsat Ground Network (LGN). Around 75 contact minutes per day are required to meet the data downlink needs for the mission, which can be achieved with ground stations located in Australia (Alice Springs, ASN) and the US (Sioux Falls, LGS)[51]. Supporting information can be found in Section 11.4.2.

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[48] Angstt.gov.au. 2021. *Network | Australian National Ground Segment Technical Team*. [online] Available at: <http://www.angstt.gov.au/network> [Accessed 22 January 2021].

[49] https://www.cyber.gov.au. 2021. *Australian Government Information Security Manual*. [online] Available at: <https://www.cyber.gov.au/sites/default/files/2021-01/Australian%20Government%20Information%20Security%20Manual%20%28January%202021%29.pdf> [Accessed 22 January 2021].

[50] https://www.cyber.gov.au/. 2021. *Australian Government Information Security Manual - Guidelines For Software Development*. [online] Available at: <https://www.cyber.gov.au/sites/default/files/2020-08/18.%20ISM%20-%20Guidelines%20for%20Software%20Development%20%28August%202020%29.pdf> [Accessed 22 January 2021].

[51] Usgs.gov. 2021. *Landsat Ground Network (LGN) Stations*. [online] Available at: <https://www.usgs.gov/media/images/landsat-ground-network-lgn-stations> [Accessed 22 January 2021].

10.9.4 Element cost estimate

The ground station network is assumed to be provided by GA, and as an in-kind contribution from USGS, and so incurs no capital expenditure. On-going operating costs for each ground station are assumed to remain constant with additional tasking, hence no operational expense would be incurred.

The development of the tasking interface is expected to cost approximately AUD0.4M. This figure is comprised of an initial development expense, followed by an on-going operational cost for the lifetime of the mission. Development expenses are not reincurred for future missions, assuming the interface is made available. GA should consider holding a license to use, or ownership of, the interface software for a series of missions. The operational cost is re-incurred for subsequent missions and is predominantly personnel focused. A cost breakdown is provided in section 11.5.2.

11 Analyses

This chapter provides detailed analyses performed during the study or evidence supporting high level information provided in the previous chapters of this report. The following sections follow a loose top-down order, but should be considered as independent chapters to be read in conjunction with the appropriate sections further up in this report.

11.1 Systems engineering analyses

11.1.1 Requirements analysis

A core part of the CDF activity consisted in a detailed derivation of mission requirements from the customer's needs. This section outlines the various levels of requirements identified in this process.

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

- **Mission objectives** as stated by the customer
- **Observation specification** as derived from the mission objectives and technical analyses into the required performance
- **Blackbox platform requirements** as derived from the observation specification to inform a small RFI campaign among satellite bus providers
- **Pathfinder mission descope** to specify areas in which the pathfinder mission may deviate from the operational missions

Their hierarchical relationship is depicted in Figure 3. The individual requirements for each specification are further detailed in the subsequent sections.

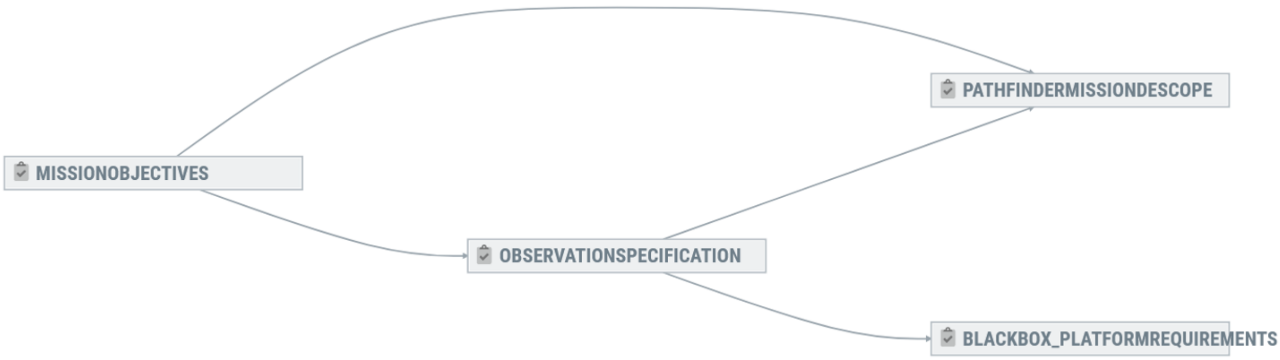

Figure 3: SCR mission specification hierarchy

11.1.1.1 Mission objectives

The following mission objectives have been identified through iterative discussions with the customer:

Table 4: SCR mission objectives

ID	Title	Description
SCR-MIS-001	Cross-Calibration	Collect coincident spectral radiometer data between cooperative optical satellite missions for cross-calibration
SCR-MIS-002	Orbit	Either: LEO optimised for cross-calibration with TBD cooperative missions Or: SSO trailing (by 20min max) one leading S/C which is one of (in order of priority): 1) Landsat, Sentinel 2 2) Planet Super Doves 3) Every other optical EO mission
SCR-MIS-003	Continuous launch	Continuous launch with annual fix funding Goal: 2 Satellites every 2 years
SCR-MIS-004	Instrument	First: Supplied through USGS (as an option) Subsequent: TBD
SCR-MIS-005	Manufacturing policy objective (bus)	Australian built
SCR-MIS-006	Manufacturing policy objective (instrument)	Hyperspectral instruments leveraging Australian niche Series of configurations
SCR-MIS-007	Launch date	Q4 2023 to a) coincide with CLARREO Pathfinder b) observe legacy landsat instrument onboard Landsat 7
SCR-MIS-008	Design lifetime	2 years (T), 5 years (G)
SCR-MIS-009	Operations concept	Contractors operating out of the GA facility in Symonston ACT to enable increased cyber security implementation

11.1.1.2 Observation requirements

Based on the above mission objectives, the mission observation requirements for the operational SCR mission have been derived. The results presented in Table 5 below are based on iterative discussions with key stakeholders from customer side and assessments of technical feasibility within the programmatic constraints for the mission. The table also lists a rationale for each requirement or a parent requirement from which it was derived.

Table 5: SCR observation requirements

ID	Title	Text	Rationale	Parents
SCR-OBS-0001	GSD VSWIR	100m	10m for AW, OzFuel 100m for USGS	SCR-MIS-001
SCR-OBS-0002	Relative orbit (if applicable)	Trail reference spacecraft by <20min and >15min	To reuse same ground station To enable cross-calibration Target missions in priority order: Landsat-8, Sentinel-2A, Landsat-9, Sentinel-2B, Super Dove	SCR-MIS-002
SCR-OBS-0003	Georeferencing accuracy	Image data shall be geo-referenced to within 1x GSD.		SCR-MIS-001
SCR-OBS-0004	Simultaneous imaging and downlink	Spacecraft shall be able to perform imaging while downlinking payload data.	To enable imaging in typical calibration sites in close proximity to ground station locations.	SCR-MIS-001
SCR-OBS-0005	Configurable payload operations	The payload operations shall allow for selecting a subset of the instrument's spectral bands to be downlinked only.	To reduce downlink data rate requirement. But it is not a desirable operational mode to account for not-yet-known applications needing specific band data.	SCR-MIS-006, SCR-MIS-004
SCR-OBS-0006	Swath location	During observations the swath shall be completely within the reference mission's swath.		SCR-MIS-001, SCR-MIS-002
SCR-OBS-0007	Swath width VSWIR	20-60km		SCR-MIS-001
SCR-OBS-0008	Spectral range VSWIR	400nm - 2400nm		SCR-MIS-001
SCR-OBS-0009	Number of bands VSWIR	100-400		SCR-MIS-001
SCR-OBS-0010	Band width VSWIR	8nm-12nm FWHM		SCR-MIS-001
SCR-OBS-0011	Radiometric accuracy VSWIR	1% to 2%		SCR-MIS-001
SCR-OBS-0012	SNR VSWIR	100-300 varying over spectral range, details are TBC		SCR-MIS-001

ID	Title	Text	Rationale	Parents
SCR-OBS-0013	Radiometric stability VSWIR	<0.2% over 30days		SCR-MIS-001
SCR-OBS-0014	Imaging duty cycle	Perform coincident observations and Cal/Val sites (T) Image all land area during daylight (G)		SCR-MIS-002, SCR-MIS-001

11.1.1.3 Preliminary platform requirements

Preliminary satellite platform requirements have been derived from the observation specification in order to support a preliminary RFI campaign among satellite bus manufacturers. It should be noted that values for the requirements have not been derived through a generic technical assessment. They rather represent an expected envelope based on the needs of a sensor such as the Ball Aerospace CHPS (see section 11.3.3 for more details). It is therefore possible that not all observation requirements listed above are able to be fulfilled with a satellite bus as specified in Table 6.

Table 6: Preliminary blackbox platform requirements

ID	Title	Text	Rationale	Parents
SCR-PF0-0001	Payload Dimensions	>200mm x >300mm x >300mm		SCR-OBS-0001, SCR-OBS-0007, SCR-OBS-0008
SCR-PF0-0002	Payload Mass	>15kg		SCR-OBS-0001, SCR-OBS-0007, SCR-OBS-0008
SCR-PF0-0003	Payload Power	>40W orbit average		SCR-OBS-0001, SCR-OBS-0011, SCR-OBS-0012, SCR-OBS-0010, SCR-OBS-0004
SCR-PF0-0004	Pointing control accuracy	60 arcsec (goal), 150 arcsec (threshold)		SCR-OBS-0003
SCR-PF0-0005	Pointing knowledge	Driven by pointing control		SCR-PF0-0004
SCR-PF0-0006	RF payload downlink frequency	X-band	Required to achieve downlink data rates	SCR-OBS-0004
SCR-PF0-0007	Payload downlink data rate	760Mbps (goal), 200Mbps (threshold)		SCR-OBS-0007, SCR-OBS-0001, SCR-OBS-0009, SCR-OBS-0002, SCR-OBS-0004
SCR-PF0-0008	On-board payload data storage	320GB (goal), 120GB (threshold)		SCR-OBS-0007, SCR-OBS-0001, SCR-OBS-0009, SCR-OBS-0002
SCR-PF0-0009	Propulsion delta-V	>100m/s	Station keeping Deorbit	SCR-OBS-0002

11.1.1.4 Pathfinder mission descope options

Finally, a key question addressed during the study was the level to which the SCR pathfinder missions shall de-risk the FOC missions. The result of this assessment is the list of acceptable descoping items presented in Table 7. Note that a pathfinder mission may accept any subset of the listed items to achieve the mission objectives.

Table 7: Areas of descope of the pathfinder mission wrt. SCR FOC mission

ID	Description
SCR-PFD-0001	The SCR pathfinder mission may provide only a subset of the observable land areas. I.e. there is no need to image and downlink every accessible location.
SCR-PFD-0002	The SCR pathfinder may perform cross-calibration by crossing passes with the reference mission. I.e., there is no need to fly in the same orbit.
SCR-PFD-0003	The SCR pathfinder may only perform imaging when coinciding with a reference mission.
SCR-PFD-0004	The SCR pathfinder mission may only create one global, annual, cloud-free mosaic of observed data.
SCR-PFD-0005	Consider reducing radiometric accuracy to 2%-3%
SCR-PFD-0006	Consider HyperScout option for SCR1 to achieve low-risk, fast-launch profile
SCR-PFD-0007	Remove need to image at the same time as downlinking payload data
SCR-PFD-0008	Consider a reference mission orbit of <600km altitude
SCR-PFD-0009	2 years

11.1.2 Trade-offs

At this early stage of the SCR mission design, several key trade-offs have been identified. Not all of them have been assessed at this stage.

- Orbit selection (linked to reference mission selection)
- Instrument design / COTS option
- Propulsion
- Number of star trackers
- Spacecraft mass range / form factor
- Payload data downlink RF band
- Spacecraft antenna concept
- Ground station locations and size
- Test model philosophy
- MOC operation staffing
- Include lateral off-nadir pointing in ConOps (as goal only)

The first 10 of the above trade-offs have been considered together for the SCR pathfinder mission. I.e. three combinations of the individual options have been created to identify a baseline system concept for the pathfinder mission. This is described in more detailed in the following section.

11.1.2.1 Pathfinder system concept trade-off

The SCR pathfinder mission can be implemented in various ways depending on the specific requirements to be descoped from the FOC mission (see sec 0). Table 8 provides three options how an implementation of the pathfinder mission could look like based on preliminary technical assessment of the combination of different trade-off elements. The selected baseline is marked in green with a simpler version and a more performant option provided for reference.

Table 8: Pathfinder implementation trade-off

Trade-off element	Reduced scope	Baseline for PF	Step-up towards FOC	Other options
Reference mission / ROM altitude	Super Dove / <600km	Landsat / 700km	Sentinel 2 / 800km	Other / <600km
Instrument	HyperScout 2	HyperScout 2	Ball CHPS, Custom-built	See sec. 0
Propulsion	No propulsion	Electrical or cold gas	Electrical	Chemical mono-propellant Chemical bi-propellant
Star tracker	1	3	3	0, 2
Form factor / mass	16U	30kg – 50kg	~100kg class	12U Photon-type
PL data downlink	X-band	X-band	X-band	S-band Ka-band Optical
S/C antenna concept	Single patch	Antenna array	Antenna array	Single patch Gimballed
Ground stations	Alice 9m	Alice 9m + USA	Alice 9m + USA	See sec. 11.4.2
System hardware models	FlatSat, SM, TM, EQM, FM	FlatSat, SM, TM, EQM, FM	FlatSat, SM, TM, EQM, FM	EM (Engineering model) PFM (Proto-flight model)
MOC operations	Business hours	Business hours	Business hours or As needed	Fully automated after handover 24/7 operations

11.1.3 Risk assessment

As part of the study, a detailed risk assessment and mitigation plan was prepared. All risks were classified on a likelihood and severity of impact scale to classify them into high, medium, and low magnitude risks as per the schema shown in Table 9.

Table 9: 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

In total, 54 risks have been identified, of which 13 were classified into one of the high-risk categories, 32 into one of the medium and 10 into one of the low risk ones. All risks with high magnitude are listed in Table 10. For these risks, mitigation actions have been identified and are listed here as well. The table also indicates if a risk is only applicable to either the Australian implementation option or the overseas option or both ("All") procurement pathways.

The highest risk item is cost and schedule blow-out due to scope creep, resulting in an unaffordable mission and cancellation.

All findings in this report are based on the defined set of mission requirements and objectives and any modification of them would have a direct impact on the mission cost, schedule and risk profile. The mission owner needs to control scope throughout the design process to help maintain the accuracy of estimates made in this study.

The mission would also strongly benefit from opportunities of partnerships with and mentorship by international partners, which can help mitigate a number of different risks.

Table 10: High risks and identified mitigation actions

Risk item	Applicable to	Likeli-hood	Impact	Mitigation actions
Mission becomes unaffordable and is cancelled	All	**Maximum**	**Catastrophic**	Agreed process and timeframes for freezing of scope.
Schedule slippage and reduced ability to effectively manage the capability development process.	Overseas	**Maximum**	Critical	Early identification and agreement on sharing of project management, systems engineering, design, construction, integration, operations, sustainment and disposal lessons-learned. Early engagement of legal advisors. Ensure time required to establish sharing frameworks is reflected in schedule.
Australian industry doesn't benefit from the mission	Overseas	**Maximum**	Major	Precise articulation of AUS industry content requirements in procurement criteria.

Risk item	Applicable to	Likeli-hood	Impact	Mitigation actions
Inability to transfer vital technical information between US and Australian stakeholders.	All	High	Critical	Ensure suitable agreements and mechanisms are part of the mission objectives. Early identification and validation of all transfer requirements by both US and AUS stakeholders. Early engagement of legal advisors.
Low stakeholder confidence in ability of Australian industry to deliver mission outcomes	AUS	High	Critical	Clear articulation of stakeholder Needs Goals and Objectives. Frequent working groups with all stakeholders, including Australian industry and experienced international partners. Development and demonstration of capability through use of 2 pathfinder missions.
Inability to overlap observations with CLARREO due launch delays.	AUS	Maximum	Major	Prime to engage closely with the LSP to be informed of on any schedule slips. Preference to be the Prime payload on launcher to avoid external schedule slips.
Stakeholder management and supply chain quality assurance	AUS	Medium	Critical	Those aspects to be reviewed to clear the gate at every Mission milestone review. Expert review committee comprised of industry experts, Agency, GA, CSIRO etc.
Spacecraft can't achieve and maintain orbits needed to make observations	All	Medium	Critical	Ensure propulsion systems reliability and capacity: validated orbit keeping requirements; heritage components; redundancy; testing, and effective propulsion management during mission operations.
Spacecraft power system fails before design lifetime	All	Medium	Critical	Ensure power systems reliability: heritage components; redundancy; testing, and effective power management during mission operations.
Failure to meet COPUOS deorbit obligations	All	Medium	Critical	Employ redundant active subsystems to facilitate deorbit; mission operations policy to accelerate deorbit schedule if subsystems degrade; use of high-drag spacecraft design to promote passive deorbit inside 25 years.
Launch failure	All	**Minimum**	**Catastrophic**	Use well established LSPs with a solid track record. If multiple spacecraft, split launches between launch vehicles and LSPs.

Risk item	Applicable to	Likeli-hood	Impact	Mitigation actions
Space craft is dead-on-arrival	All	Minimum	Catastrophic	Rigorous, appropriate and relevant test campaign with focus on LEOP. Pathfinder timeline with suitable time to apply lessons-learnt to FOC
Collision with other A-train spacecraft	All	Minimum	Catastrophic	Separation of orbits. Redundant, heritage propulsion. Well defined mission operations policy and process with access to appropriate space situational awareness information. Manoeuvre coordination with reference missions.

Medium risks are listed in the table below. With the limited time during the study a mitigation strategy has only been identified for some of the risks. As this work is not complete, it is not described in detail.

In general, the medium risks are more of a technical nature than the high risks and many of the mitigation strategies identified for the high risks will have beneficial mitigative effects on the lower magnitude risks as well. Cyber-related risks have been assessed as medium magnitude with a cyber attack on the space segment having mission-critical impact, but with existing best-practices of encryption, authentication and authorization being of minimum likelihood.

Table 11: Medium risks identified

Risk item	Type	Likeli-hood	Impact	Comment
Low TRL of AUS instrument	Programmatic	High	Major	Pathfinder procurement options
On-board calibration system not able to demonstrate performance stability over lifetime (low TRL)	Technical	High	Major	Technology de-risk opportunity
High data rate downlink radio (low TRL)	Programmatic	High	Major	mitigation actions identified
Radiometric accuracy below spec	Technical	High	Major	Technology de-risk opportunity
Project over budget	Programmatic	High	Major	mitigation actions identified
Knowledge gap in building operational Avionics/Resilient Systems	Programmatic	High	Major	AUS-made only, mitigation actions identified
Skills retention throughout pathfinder missions	Programmatic	High	Major	
Ground station tasking conflict due to A-Train orbit	Technical	High	Significant	
Small pool of experienced personnel in Australia making system reviews less beneficial	Programmatic	High	Significant	
ITAR if using Rad Hard / JAN-TX parts from US Vendors	Programmatic	High	Significant	

Risk item	Type	Likeli-hood	Impact	Comment
Space segment not ready for launch on schedule	Programmatic	High	Significant	
Spec doesn't demonstrate transfer cross-calibration	Technical	Medium	Major	
Launch delay due to launch provider	Programmatic	Medium	Major	Overseas only
Pathfinder failure impacting FOC mission	Programmatic	Medium	Major	
Environmental AIT facility readiness/capacity	Programmatic	Medium	Major	AUS-made only
Procurement flexibility to account for on-going tech developments over programme	Programmatic	Medium	Major	
Little heritage in 30-50kg S/C size	Programmatic	Medium	Major	AUS-made only
Unable to achieve precise orbital injection/required orbit	Technical	Low	Critical	
Failure of the on-board anomaly handling software	Technical	Low	Critical	mitigation actions identified
Specifying and developing a representative Pathfinder within Budget/Schedule	Programmatic	Low	Critical	
Failure of onboard calibration system (HSI aperture blocked)	Technical	Low	Critical	
Use of component which removes partner involvement in mission	Political	**Minimum**	Critical	
Optics system contamination in-orbit	Technical	**Minimum**	Critical	
Cyber attack on spacecraft	Programmatic	**Minimum**	Critical	mitigation actions identified
Spec doesn't demonstrate independent cross-cal	Technical	Low	Major	
General failure of onboard calibration system	Technical	Low	Major	
Spacecraft put in an unsafe state due to errors in automated scheduling software	Technical	Low	Major	mitigation actions identified
Partial or full ADCS failure degrades pointing performance for imaging and GS communications	Technical	Low	Major	mitigation actions identified
Use of component which removes partner ground station opportunities	Political	Low	Major	
Instrument design inherently unable to meet radiometric accuracy req't	Technical	Low	Major	

Risk item	Type	Likeli-hood	Impact	Comment
HSI imager not meeting operational lifetime	Technical	Low	Major	
Cyber attack on ground segment (GS and processing chain)	Programmatic	Low	Major	mitigation actions identified

The table below lists risk items of low magnitude as identified in the study. Again, many of them will benefit from mitigation actions identified for high-risk items above.

Table 12: Low risk items identified

Risk item	Type	Likeli-hood	Impact	Comment
Lack of suitable AIT/optical integration facilities on-shore	Programmatic	Medium	Significant	
In-orbit commissioning phase takes longer than expected/scheduled due to unplanned issues.	Programmatic	Medium	Significant	
Incompatibility when interfacing L0 processor to L1/schedule risk in building an L0 processor in Australia	Programmatic	Medium	Significant	
Implementation of on-board data management	Technical	Medium	Significant	
Blackbox subsystems with inadequate support	Technical	Medium	Significant	Overseas only
Propulsion system doesn't meet specifications	Technical	Medium	Significant	AUS-made only
Delays in developing L2/L3 processing system	Programmatic	Low	Significant	
Ability to meet and prove requested operational on-orbit lifetime	Technical	Low	Significant	
Space weather event	Technical	**Minimum**	Major	
Unchartered Regulatory Regime (Insurance + Misc)	Programmatic	**Minimum**	Major	

11.2 Mission operations

11.2.1 Concept of operations

The SCR mission Concept of Operations (ConOps) relies on two operational modes:

- The default mode is to perform imaging during predefined intervals of coincident observations.
- A secondary mode consists in the continuous imaging of all land cover.

In the default mode, the opportunities for coincident observations are computed on ground based on the ephemerides of all cooperative missions. The results of this computation are then used to define the satellite's imaging schedule. In a first order, this operational mode would fulfill all immediate needs for image acquisition while keeping the data volume to downlink to ground to a minimum.

The second mode would allow to store image data in a ground archive for future use. This can serve use cases that are currently not identified but may become of interest in the future. Since this mode leads to a significant increase in the payload data budget, it shall only be implemented to the extent that it does not drive the system design.

With either of the two operational modes it shall be possible to perform imaging while downlinking payload data to a ground station. This would define a dedicated spacecraft mode with potentially challenging implications for the power budget, on-board payload data handling and antenna design.

Imaging operations would be interrupted on a regular basis to perform instrument calibration. This may come in several forms: Vicarious, lunar, solar or on-board calibration. Further details on the calibration approach can be found in section 11.3.2.

The implementation of the SCR ground segment would leverage the expertise and capabilities of the Australian National Ground Segment Technical Team (ANGSTT). This ensures application of best practices in line with other national space programs and avoids unnecessary cost.

All communications between space and ground segment would employ encryption, authentication and authorisation following best practices from the Australian Signals Directorate (ASD) Information Security Manual and others if applicable.

Further details on the data processing pipeline including how external stakeholders would be able to interface with the different subsystems is provided in section 11.5.3.

To maximise the public impact of the SCR mission, non-sensitive details of the mission telemetry would be made available to relevant space educational institutions after a GA training. These include, but are not limited to the Agency's Australian Space Discovery Centre (ASDC), Victorian Space Science Education Centre (VSSEC), Mount Stromlo Space and STEM Education centre and others.

11.2.2 Mission operations centre

The SCR MOC has been introduced in section 10.8. This section provides further details.

Specifically, required infrastructure for the MOC would include:

- 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 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 an SCR series spacecraft;
- a filterable cloud-based database of communications between the ground stations and SCR series spacecraft. This database includes all commands that are uplinked and all responses

that are received, including housekeep telemetry, configuration data, payload data, and spacecraft log files;
- methods to set warning limits for telemetry fields so that operators can be immediately notified of non-nominal spacecraft health;
- software tools for visualisation and trending of spacecraft telemetry;
- methods to export and share telemetry and payload data in accessible formats.

Significant up-front development is required for the MOC prior to the first SCR series pathfinder, after which only updates and maintenance are required for continued reliability and compatibility with later missions. An initial investment in operations development is expected to pay off with reduced operational costs after launch and greater mission outcomes. The MOC would be used for on-orbit operations, operator training, and as discussed in section 10.8, system level testing before and after launch.

Table 13 lists the elements of the MOC and their estimated costs. The assumptions made in this cost estimate are:

- the software infrastructure would be developed from the ground up, or substantial modification would need to be made to an existing infrastructure to support the mission;
- a moderate level of automation would be built into the operations software, as described in section 10.8.1;
- operations staffing is restricted to business hours, with the exception of the launch and early orbit period (LEOP);
- staffing costs are AUD200k per person per annum, including overheads.

Table 13: Breakdown of MOC cost estimate

Item	Staffing (person months)	Cost (MAUD)
TT&C handling	42	0.7
Automated spacecraft tasking software	96	1.6
Operator training	33	0.6
Mission operations	72	1.2
Total	**243**	**4.1**

11.2.3 Sustainability of operations concept

To reduce the accumulation of space debris, Earth-orbiting missions must be designed to 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[52] states that a spacecraft with a perigee altitude below 2000 km shall 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 are unable to re-enter naturally 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 deorbit 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 mission while the spacecraft bus is still functional. If a failure occurs to a critical platform

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

component during the mission, it may not be possible to command the deorbit manoeuvre and the spacecraft would not 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[53]. With this in mind, we any SCR series spacecraft that are launched to trail Landsat or Sentinel 2 satellites must be designed and tested for high reliability over the mission lifetime to mitigate the risk of creating space debris in a highly populated 700-800 km altitude polar orbit. We recommend that any pathfinder missions target an orbit of less than 600 km altitude.

All planned, confirmed, and cancelled manoeuvres for orbit insertion, station keeping, would be reported to the 18th Space Control Squadron (18 SPCS) as per 18 SPCS's Spaceflight Safety Handbook for Satellite Operators[54]. Additionally, regular ephemeris data from the on-board GPS would be supplied to 18 SPCS to improve the accuracy of the catalogue entries and conjunction assessments for the SCR series spacecraft.

11.2.4 Orbit mechanics and propulsion requirements

As discussed in section 9.4, the SCR orbit has not been completely defined at this stage. Nonetheless, this chapter provides some supporting analyses to facilitate orbit selection and inform the design of a propulsion subsystem for the SCR mission.

The need for on-board propulsion for the SCR mission may be driven by two operational needs:

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

The 25-year goal can be achieved by leveraging atmospheric drag of a spacecraft. For typical micro- or nano-satellites this is possible at orbital altitudes below ~600km - ~650km. At higher altitude the atmospheric density would not be able to provide sufficient drag to achieve the desired re-entry timeframe.

Station acquisition may become important in the case that the SCR satellite is launched as a secondary payload and the primary payload on that launcher is targeting an orbit which is not suitable for SCR. It may be required to manoeuvre the SCR spacecraft to the final orbit on its own accord.

Station keeping may be required if flying in formation with another satellite that has different aerodynamic properties so that a natural drift would accumulate over time. In this case, propulsion would be needed in regular intervals to keep the relative orbital position.

The total impulse required for deorbit 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 in a station keeping scenario only small adjustments are required. Figure 4 maps the required delta-V for a Hohmann transfer between an initial orbit of given altitude and a given altitude change. It should be noted that utilising Hohmann manoeuvres in the LEO region yields an error of <<5% even if compared to realistic continuous low-thrust manoeuvres. The plot shows that to move a satellite from a 700km orbit to a 500km passive re-entry orbit would require ~100m/s delta-V.

[53] US Government, 2019, Orbital Debris Mitigation Standard Practices, https://orbitaldebris.jsc.nasa.gov/library/usg_orbital_debris_mitigation_standard_practices_november_2019.pdf
[54] 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.

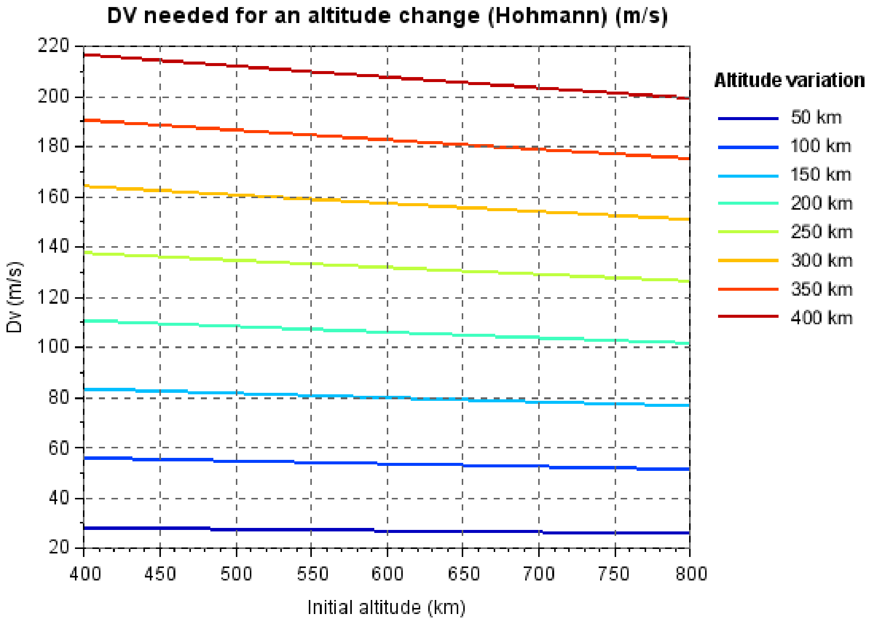

Figure 4: Circular-to-circular orbit manoeuvre delta-V requirement as function of initial orbit altitude and change in altitude

The required mission delta-V in combination with the selected propulsion technology would determine the mass fraction of the propellant in relation to the satellite's dry mass. This relationship is plotted exemplarily for a 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. To continue the above example: For a 100m/s mission, a cold gas system would require ~10% (=5kg) of propellant, while an electrical system would need <1% (=0.5kg).

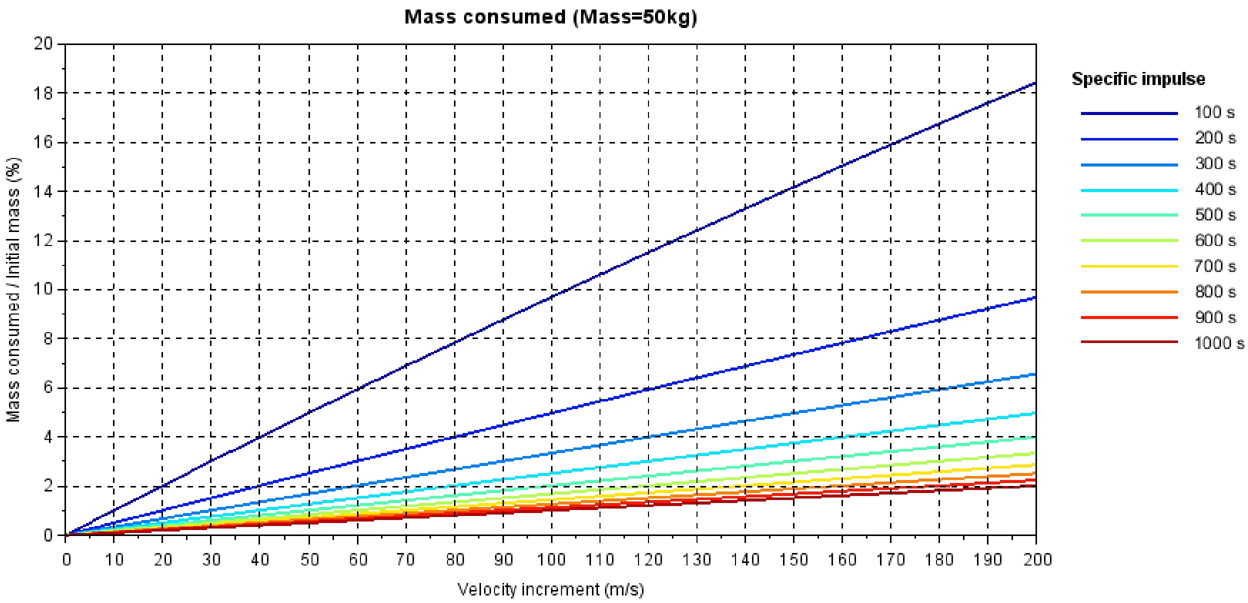

Figure 5: Propellant mass fraction depending on delta-V and specific impulse of propulsion subsystem

While fuel efficiency increases for higher Isp propulsion subsystems, thrust decreases. Typical thrust levels for Hall-effect thrusters (Isp ~1000s) are in the order of a few mN. This leads to the need of a substantial period of time for thrusting to achieve a certain orbit change. Continuing the above example, performing a manoeuvre of 100m/s using a thruster with 1.8mN of thrust requires ~3E6s or 35 days of continuous thrusting as plotted in Figure 6. This does not consider the fact that typically there is not enough electrical power available during orbital eclipse, which would naturally extend the required period by a factor of ~1.5.

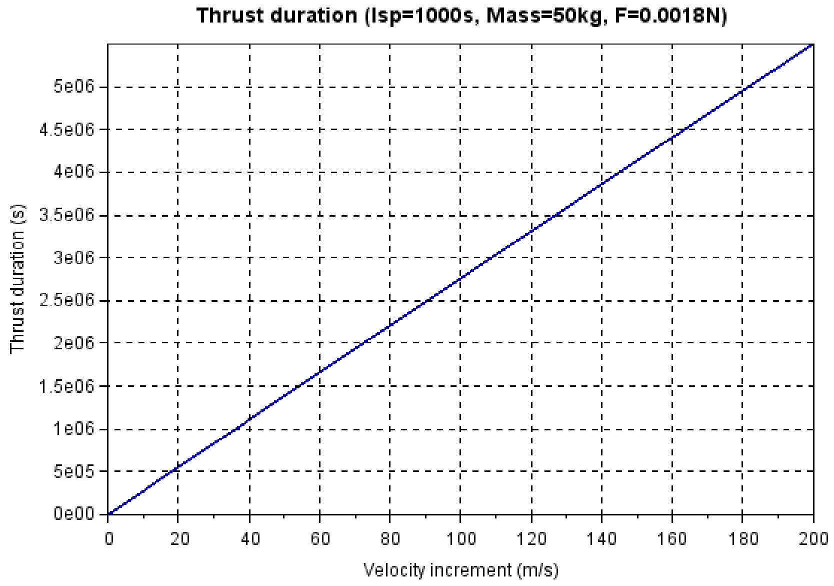

Figure 6: Thrust duration as function of delta-V for a 1.8mN thruster on a 50kg satellite

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

11.3 Payload assessment

11.3.1 Payload performance

The radiometric accuracy and cross-calibration mission objectives drive the instrument spectral, spatial, and radiometric resolution performance capabilities.

The SCR instrument requirements were summarised in section 11.1.1.2. In general, the instrument would deliver the following performance capabilities with threshold (T) and goal(G) values noted:

Table 14: SCR instrument capabilities

Performance parameter	Value
GSD (m)	100 (T) < 100 (G)
Spectral range (nm)	400 - 2400
Spectral resolution (nm)	8 (T) (FWHM bandwidth)
Band centre wavelength spacing (nm)	10
Number of bands	200 (based on 10 nm spacing and spectral range)
Radiometric accuracy absolute (%)	1(G), 2(T)
Radiometric resolution (mW/(m2-sr-um))	0.1
SNR	100-300:1; band dependent

The SCR FOC will necessarily be a high-performance instrument in the same class as CLARREO Pathfinder (e.g. spectrally resolved Earth reflectance <0.3%) and will require significant science community input and engineering expertise to develop. Consider that the radiometric and spectral accuracy requirements for SCR are more demanding than even the best space-based state-of-the-art hyperspectral imaging spectrometers currently in operation. For example, both PRISMA and EnMap have an on-orbit absolute radiometric requirement of 5% and a stability requirement of 2.5%. SCR will have requirements on the order of 1% for both. EnMap and PRISMA spectral sampling and bandwidth capability represent the current best achievable at ≤ 10nm[55] and ≤ 14 nm[56], respectively. Both systems have a spectral calibration accuracy requirement of 0.1 nm[57].

SCR will ideally provide a better level of performance and have similar spectral calibration requirements and more stringent radiometric calibration requirements. But the instrument development will also need to consider the optical, mechanical, thermal and electrical design challenges that the radiometric performance and calibration requirements will impose.

[55] Baur, S., et al., “Calibration and characterization of the EnMAP hyperspectral imager”, Proc. SPIE 11151, Sensors, Systems, and Next-Generation Satellites XXIII, 111511B (10 October 2019); doi: 10.1117/12.2532715

[56] Camerini, M., et al., "The PRISMA hyperspectral imaging spectrometer: detectors and front-end electronics", Proc. SPIE 8889, Sensors, Systems, and Next-Generation Satellites XVII, 888917 (16 October 2013); https://doi.org/10.1117/12.2030409

[57] Meini, M., et al., “Hyperspectral Payload for Italian PRISMA Programme”, Optical Payloads for Space Missions, John Willey and Sons, 2016 10.1002/9781118945179

11.3.2 Payload calibration

The SCR mission objectives for calibration would be the same as for example CLARREO Pathfinder[58] or TRUTHS where SCR would conduct on-orbit SI-traceable calibration[59] of spectral scene radiance/reflectance at an improved accuracy over other sensors and to use that improved accuracy as a 'gold standard' reference for inter-calibration of other sensors such as Landsat, Sentinel-2 and others.

Accuracy and stability requirements for satellite measurements in the reflected solar and SWIR bands are necessarily stringent for climate and weather applications and satellite sensor cross-calibration. Calibration requirements that are traceable to SI standards would be imposed such that tools for characterizing the geometric, radiometric and spectral performance of SCR and for generating correction parameters to be applied to the datasets can be adequately developed. As such, this requires exacting pre-launch and post-launch instrument calibration and validation.

The characterization and calibration of SCR would be planned and implemented in conjunction with the instrument development to meet the overall performance requirements. Since SCR requirements place much greater demands on the uncertainty of sources and delivery systems for calibration this necessitates the use of existing state-of-the-art facilities for on-ground calibration. In addition, on-board calibration subsystems whether these be passive-solar or active-spectral source based will be required to maintain very low uncertainties in radiometric output, uniformity and stability.

Maintaining a valid set of instrument response function (IRF) calibration and correction parameters that account for any anomalies or overall performance degradation over time is an operational imperative for tracking the radiometric, spectral and geometric response of the instrument. This mission critical activity begins with the pre-launch calibration and continues throughout the mission life with regularly scheduled in-flight calibration operations.

11.3.2.1 On-Ground Calibration

The goal of the on-ground calibration campaign is to establish a pre-flight IRF reference. Ground support facilities that provide high-accuracy and SI-traceable radiometric, spectral and geometric stimuli provide the means to establish the IRF with a high degree of certainty prior to launch.

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

The SCR would be calibrated and characterised at instrument level in a well-established facility which is explicitly designated for space-based optical instrument calibration. A facility such as NASA's GLAMR (https://glamr.gsfc.nasa.gov/) which provides the stable and accurate radiometric and spectral sources (and will be used for the calibration of CLARREO Pathfinder) would be an ideal candidate for the on-ground calibration of both the SCR FOC (and the SCR PF if needed).

In addition to radiometric and spectral calibration, an image quality assessment at instrument level would also be performed where key parameters such the instrument imaging response functions (e.g. modulation transfer function) would be determined using an appropriate set of targets and delivery systems. In addition to the SCR image quality, the pointing of the instrument with respect to the spacecraft axes would be established so that geo-referencing requirements are met.

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[58] Thome, K., and Aytac, Y., "Independent calibration approach for the CLARREO Pathfinder Mission, Proceedings Volume 11130, Imaging Spectrometry XXIII: Applications, Sensors, and Processing; 111300B (2019) https://doi.org/10.1117/12.2529215
[59] Datla, R.U., et al., "Best Practice Guidelines for Pre-Launch Characterization and Calibration of Instruments for Passive Optical Remote Sensing", J. Res. Natl. Inst. Stand. Technol. 116, 621-646 (2011).

11.3.2.2 In-Flight Calibration

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

Periodic in-flight calibration of all spectral channels provides the means to correct the instrument responsivity that accounts for the likely performance degradation of the optical and detector components, which can occur in the space environment. Internal calibration of the instrument as well as vicarious calibration campaigns imaging terrestrial and lunar sites and cross-calibration with other instruments (e.g. CLARREO Pathfinder, EnMaP, PRISMA) should be performed to provide a comprehensive evaluation of the SCR response over the mission life.

An on-board calibration sub-system provides known and accurate radiometric input. The instrument response to these sources links every spectrometer terrestrial dataset and provides the means for conducting trend analysis to monitor spectrometer performance over time.

The on-board calibrators, vicarious calibration and cross-calibration campaigns with other sensors in conjunction with the instrument performance models and laboratory calibration baselines provide the means to maintain a traceable instrument response as well as image product validation over the mission. This approach is summarised in Figure 7.

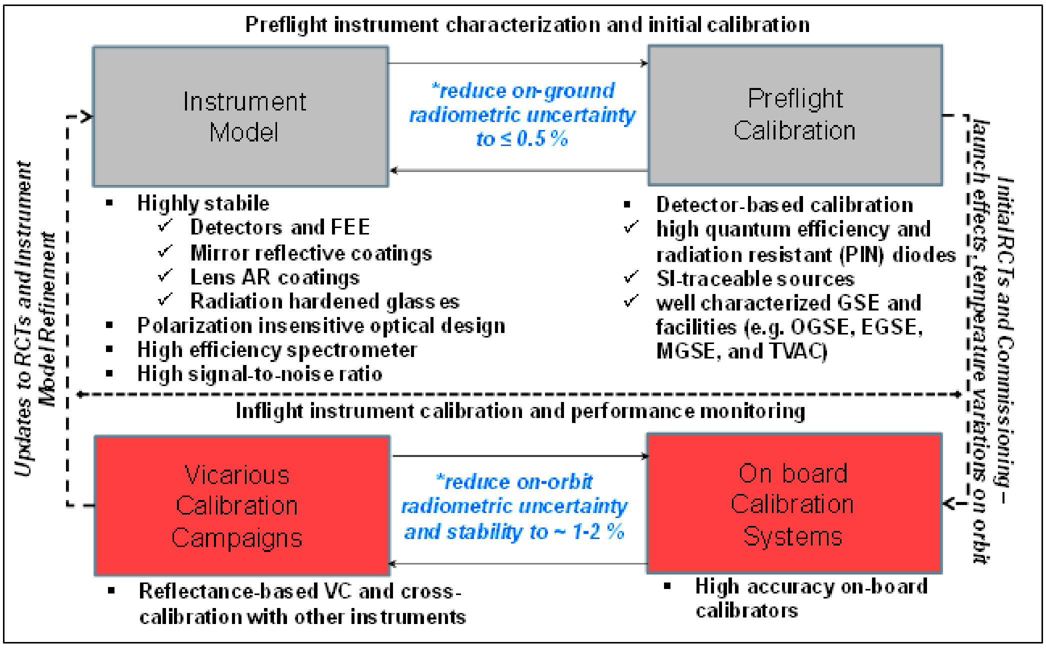


Figure 7: SCR lifecycle radiometric calibration approach overview

Typically, a solar calibration unit will be included as part of the instrument design. The sun provides a stable source, which establishes the absolute radiometric accuracy and stability assessments of the spectrometer during the mission life[60]. The solar calibration unit provides a full-aperture calibration of the entire optical chain from the optical system entrance aperture to the detectors to account for any changes in transmission and sensor response.

In addition, active LED lamp sources are used to provide an assessment of the spectrometer spectral response over time. The delivery system which is incorporated into the spectrometer design should provide an athermal environment for the sources as well as stable and steady drive current. Any diffusers should be protected from radiation and thermal variations when not deployed in order to

[60] Baur, S., et al., "Calibration and characterization of the EnMAP hyperspectral imager", Proc. SPIE 11151, Sensors, Systems, and Next-Generation Satellites XXIII, 111511B (10 October 2019); doi: 10.1117/12.2532715

maintain their stability. Despite these design practice implementations, the lamps themselves can change in colour temperature over time and diffuser material scattering properties can change due to the harsh space environment.

In addition to radiometric calibration operations, the acquisition of designated terrestrial targets would be used to assess the SCR in-flight measurement of spatial resolution parameters, including ground sample distance, far field response, edge response and modulation transfer function as well as geo-reference accuracy. These acquisitions would be part of normal calibration operations over the mission life[61].

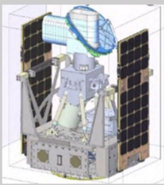
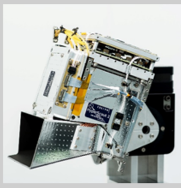
11.3.3 Payload options

Several options were considered for a SCR PF and SCR FOC mission. A review of the currently available off the shelf instruments and those being designed for use to support the Sustainable Landsat Imaging program was conducted. The results are summarised in Table 15 which provides a checklist of performance capability against the preliminary requirements (Table 5). Green ticks indicate compliance with the observation requirements, red font indicates non-compliance. At this stage, no distinction is made between partial and non-compliance. For example, while the ANU VIS and Eartheye sensors provide a SNR >100 across all bands, they do not achieve the expected required SNR closer to 300 in some critical bands. This has not been analysed in detail, but should be done in a future design study.

Ball Aerospace in partnership with NASA is developing systems such as the REMI-AB and CHPS-AB instruments. These have recently completed airborne testing flights[62]. The CHPS sensor is considered to be the currently best available candidate for the SCR FOC.

Another possibility for use on the SCR PF could be the Micro-HyperSpec from Headwall Photonics. This would be investigated in the next phase of the project along with the HyperScout2 for inclusion on a SCR PF mission.

Table 15: Payload options performance overview

	 Ball CHPS	 HyperScout2	ANU developments (can be combined)		Eartheye
			VIS	SWIR	
Spectral range	✓	400nm-1000nm	400-800	800-2500	450nm-2400nm
Spectral resolution	✓	✓	✓	(✓) TBC	9nm – 24nm
Swath width	✓	✓	10-30km	10-20km	30km (@ >900nm)
Spatial resolution	?	✓	✓	✓	✓
Radiometric accuracy	?	~5%	?	?	3% - 5%
SNR	?	<100	>100	(✓) TBC	>100
TRL	?	9	4	4	6/7

[61] Pagnutti, M., et al., "Targets, methods, and sites for assessing the in-flight spatial resolution of electro-optical data products", Canadian Journal of Remote Sensing 36(5):583-601 2010.

[62] https://www.ball.com/aerospace/newsroom/detail?newsid=124032

11.3.4 Payload data handling

The SCR spacecraft hyperspectral imager may generate copious amounts of data depending on the duty cycle, number of spectral bands used, and other properties of the instrument itself. As a guide, the table below presents trade-off options in reference to GSD, and swath width of the imager.

Table 16: Daily data volume estimate for various combinations of GSD and swath width

Daily data volume [GB/d]	**GSD [m]**			
Swath width [km]	**100**	**50**	**30**	**10**
10	14	58	160	1444
20	29	116	321	2889
40	58	231	642	5778
60	87	347	963	8667
80	116	462	1284	11556

The figures are based on the following assumptions:

- 16.5% duty cycle (worst case)
- 12 bits per pixel
- 100 spectral bands
- 705km orbit altitude
- 75min/day of GS contact time

The numbers in cells with grey background colour indicate configurations that exceed the limit imposed by existing ground segment data processing capabilities, which are in the order of ~500TB/year. Red font colour indicates configurations that exceed the expected maximum across-track detector size at 2000 pixels.

Once the instrument is selected, the swath width, GSD, number of spectral bands and other properties of the instrument would determine the final data volume per day the spacecraft would need to manage.

On board data handling consists of storing the payload data into non-volatile memory with appropriate meta information such as timestamps and location telemetry. The data is then potentially compressed and sent to the high bandwidth radio transmitter for downlink. Special precautions and data handling architecture should take into account how simultaneous reading and writing from non-volatile memory should be handled. This situation may arise when the spacecraft is imaging while downlinking data to the ground station.

11.4 Satellite platform subsystems

11.4.1 Communications

The spacecraft shall have a number of communication channels, some capable of both uplink and downlink while others supporting only downlink functions.

The primary communication channel for telemetry and telecommand can be a low bandwidth channel supporting at least 9.6 kbps data rates in both uplink and downlink directions. The secondary or redundant telemetry and telecommand communication channel would be preferred and this communication channel shall also support uplink and downlink data rates of at least 9.6 kbps. The primary and secondary T+TC channels should use UHF and/or S-Band frequency bands and should provide omni-directional antennas so that communication with the spacecraft can be established whilst the spacecraft are in any orientation.

The payload downlink communication channel shall be a high data rate communication channel in the S-Band or preferably X-Band frequency range. These frequency ranges allow the use of existing ground station infrastructure hence greatly reducing the cost of obtaining the data from the spacecraft by leveraging existing infrastructure and partnerships.

The payload downlink channel requires a minimum bandwidth of 200 Mbps in order to allow downlinking sufficient volumes of data. This communication channel shall have some form of redundancy, even if it means the redundancy is bandwidth reduced.

11.4.2 Power

The spacecraft shall provide sufficient power generation capability to ensure the power budget remains positive throughout all the commissioning and nominal operations. The power generation shall be implemented using triple junction solar cells. Depending on the spacecraft bus and the payload power requirements, as well as the final mechanical configuration of the spacecraft, deployable solar arrays may be necessary.

The spacecraft shall provide power sufficient power storage capability to support spacecraft operations through eclipse periods and to supplement power generation sources in high power operations. Commonly used energy storage element are batteries, in lithium or other chemistries depending on operational and environmental requirements. The energy storage element shall be capable of supplying the required surge currents (peak and continuous) and shall be sized appropriately so that it is not discharged beyond safe limits during eclipse and high power operations (this is typically a maximum discharge of 20% for lithium based chemistries).

11.4.3 Flight software elements

The flight software of a spacecraft can be classified into two groups: core/platform software, 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 OBC (for TT&C of the payload) and with the payload radio (for downlink of payload data). Well-functioning software is critical to mission success and can result in a total loss of mission if an error occurs. The following standards are relevant when delivering high quality software:

- ISO 49.140 (particularly ISO 14950)
- ISO 25010
- NASA-HDBK-2203
- NASA-STD-8739.8
- NASA-GB-8719.13

11.4.3.1 Platform software

The platform software is often (but not always) provided by the spacecraft bus provider. The capabilities of the software provided depend on what has been agreed upon via the contract. The platform software is required to enable 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

11.4.3.2 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 for defect correction and feature additions to take place post-launch. We recommend ensuring that all relevant subsystems can be reprogrammed in-orbit.

11.4.3.3 Common procurement options

Various options for the scope and deliverables of the software package exist. Common options are listed below.

Table 17: Software package overview and qualitative, 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 the software to their TT&C requirements or make appropriate adjustments to the ground-based systems.	$$
Whole mission application	Drivers and framework, as well as any specific NRE required for the mission. This includes the integration of the payload software with the platform OBC, and any integration required between the payload OBC to the payload radio.	$$$$

11.5 Ground segment analyses

11.5.1 Ground station network

The following ground station sites were considered as viable candidates for the mission.

- Alice Springs, NT, Australia (-23.758970, 133.881859)
- Hobart, TAS, Australia (-43.057600, 147.317783)
- Cape Ferguson, QLD, Australia (-19.269191, 147.054298)
- Learmonth, WA, Australia (-22.234866, 114.094383)
- Sioux Falls, SD, USA (43.735932, -96.622455)
- Hartebeeshoek, South Africa (-25.887705, 27.706159)
- Davis Station, Antarctica (-68.576664, 77.967653)
- Svalbard, Norway (78.217, 15.65)

A preliminary analysis of the suitability of various combinations of these ground stations in a SCR ground station network has been performed. Figure 8 shows the coverage of each of the listed ground stations for an exemplary satellite in a 700km SSO.

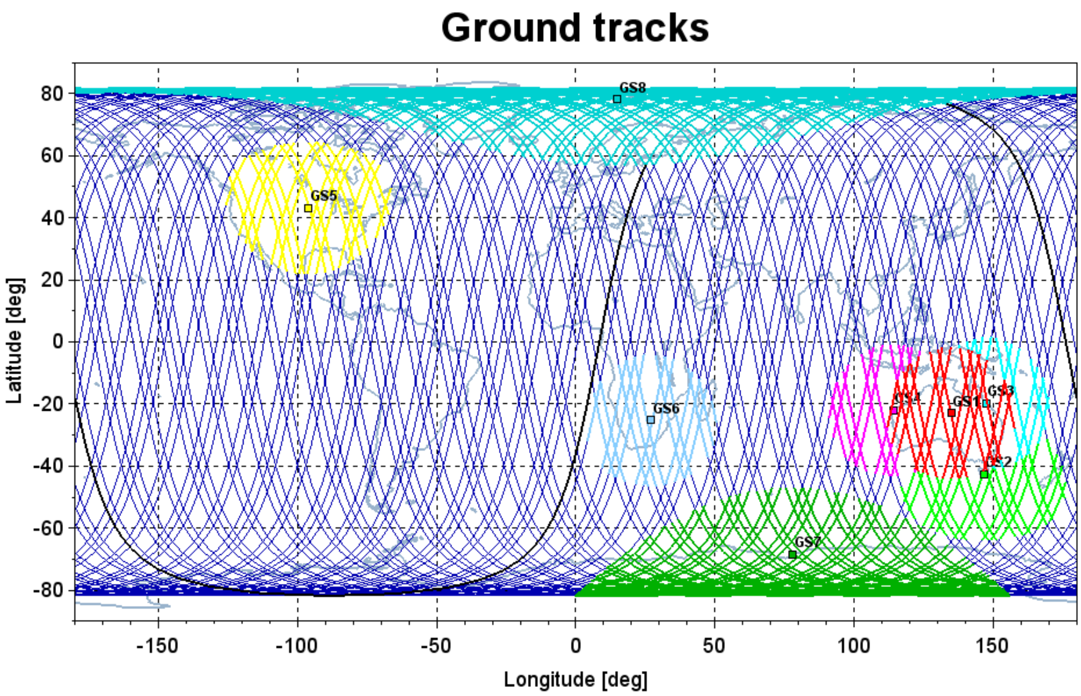


Figure 8: Orbital coverage of candidate ground stations

The resulting daily contact times are provided in Table 18.

Table 18: Ground station network options and associated daily contact times

Station combination	Total visibility (min/day)	Comment
Alice Springs	35	AUS only
Hobart	45	AUS only
Alice Springs, Hobart	52	AUS only
Alice Springs, Hobart, Christmas Island	82	AUS only
Alice Springs, Hobart, USA	102	
Alice Springs, Hobart, USA, South Africa	131	
Alice Springs, Hobart, USA, South Africa, Antarctica	223	
Alice Springs, Learmonth, Cape Ferguson	63	AUS only
Alice Springs, Learmonth, Cape Ferguson, USA	108	
Alice Springs, Learmonth, Cape Ferguson, USA, South Africa	141	
Alice Springs, Learmonth, Cape Ferguson, USA, South Africa, Antarctica	227	
Alice Springs, Learmonth, Cape Ferguson, Hobart	76	AUS only
Alice Springs, Learmonth, Cape Ferguson, Hobart, Antarctica	168	AUS only
Alice Springs, USA	75	
Alice Springs, USA, Antarctica	167	
Alice Springs, USA, Svalbard	229	

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 provides a significant increase in contact time. A USA station adds ~40 min/day, with an Artic station adding ~147 min/day.

An Antarctic station adds ~90 min/day. Today, Antarctica has no undersea connectivity, due to the data rates of this mission backhaul via bandwidth-constrained satellite links would likely not be viable. An undersea cable would need to be provisioned if Antarctica is to be used for bulk payload data downlink. Such an Antarctica cable would need to be high availability as it would likely be the main ground station for this mission and the cable should be a high data rate to ensure timeliness of the data products. To meet the availability requirements multiple TT&C capable ray dome shielded ground stations would be required in Antarctica for redundancy to allow for station maintenance and potential outages.

As shown above, an Arctic station adds a significant amount of contact time. Most Arctic stations are commercially operated, which can bring about contractual and operating expenditure issues.

11.5.2 Ground segment cost assessment

The ground segment contracted cost is estimated at AUD0.4 M based on an FTE-year costed at AUD200k. Details are provided in Table 19.

Table 19: Ground segment cost estimation details

Aspect	FTE	Duration [months]	FTE-months
Scoping / design	1	3	3
Development	1	6	6
Verification and validation	1	3	3
Maintenance and support	0.5	24	12
Total			**24**

11.5.3 Processing pipeline

The following table provides an overview of elements in the processing pipeline together with an indication of the responsible entity for software development and operations of each element.

Table 20: Overview of processing pipeline elements

Task	Software development	Operations	Notes
MoC/ TT&C	Contractor	Contractor	
Ground Station	GA/Partner	GA/Partner	In-network Predefined TT&C commands sent by contractor
Stitcher	GA	GA	In-network
L0	Contractor	GA	In-network Collections: Ground station telemetry, mission telemetry
L1	GA	GA	In-network Open product Collections: L1 product
L2 (ARD)	GA	GA	In-network Open product and code Option 1 collections: CARD4L surface reflectance, L2 cross-calibration product Option 2 collections: CARD4L surface reflectance, L2 cross-calibration product, bushfire fuel ancillary, L2 bushfire fuel product, water quality ancillary, L2 water quality product, L2 minerals indices
L3	GA/Partner	GA	In-network Open product and code Option 1 collections: L3 cross-calibration product Option 2 collections: L3 cross-calibration product, L3 bushfire fuel product, L3 water quality product, L3 minerals indices
Data distribution for L1/L2/L3	GA	GA	Via GA or AusCopHub

11.5.3.1 Stitching Background

Processing pipelines (Products from the NASA Data Processing Levels) are well understood within the Earth observation community, but ground station stitching is not often undertaken for land imaging missions hence additional background is required.

Ground reception stations can only receive data when the spacecraft is in line of sight, and that is successful only if there are no equipment malfunctions, radio frequency interference, or conflicts with other higher priority spacecraft. A network of reception stations can overcome, or mitigate, these limitations by extending the spatio-temporal coverage of reception and providing multiple pathways to receive the data. Stitching realises the opportunity afforded by a ground station network to deliver the back-end ground processing required to merge the data streams from the spacecraft.

The objective of stitching is to create the most complete and highest possible quality Level-0 data stream in the shortest possible time after spacecraft overpass. In addition, this process could be used to create near-real-time quicklook images.

The Australian National Ground Station Technical Team operates a ground station stitching network for the AVHRR, MODIS and VIIRS sensors received by ground stations within their network. The software to perform the merging was developed at CSIRO in the late 1990s and has been in continuous operation ever since.

An example for the results of the stitcher is provided in Figure 9. The imagery are shown in satellite (swath) projection. The coast of Western Australia is visible in the right-hand side of each scene, north is towards the top. Note that the final stitched pass is both longer and does not contain the missing lines evident at the southern end of the Darwin and Alice Springs passes.

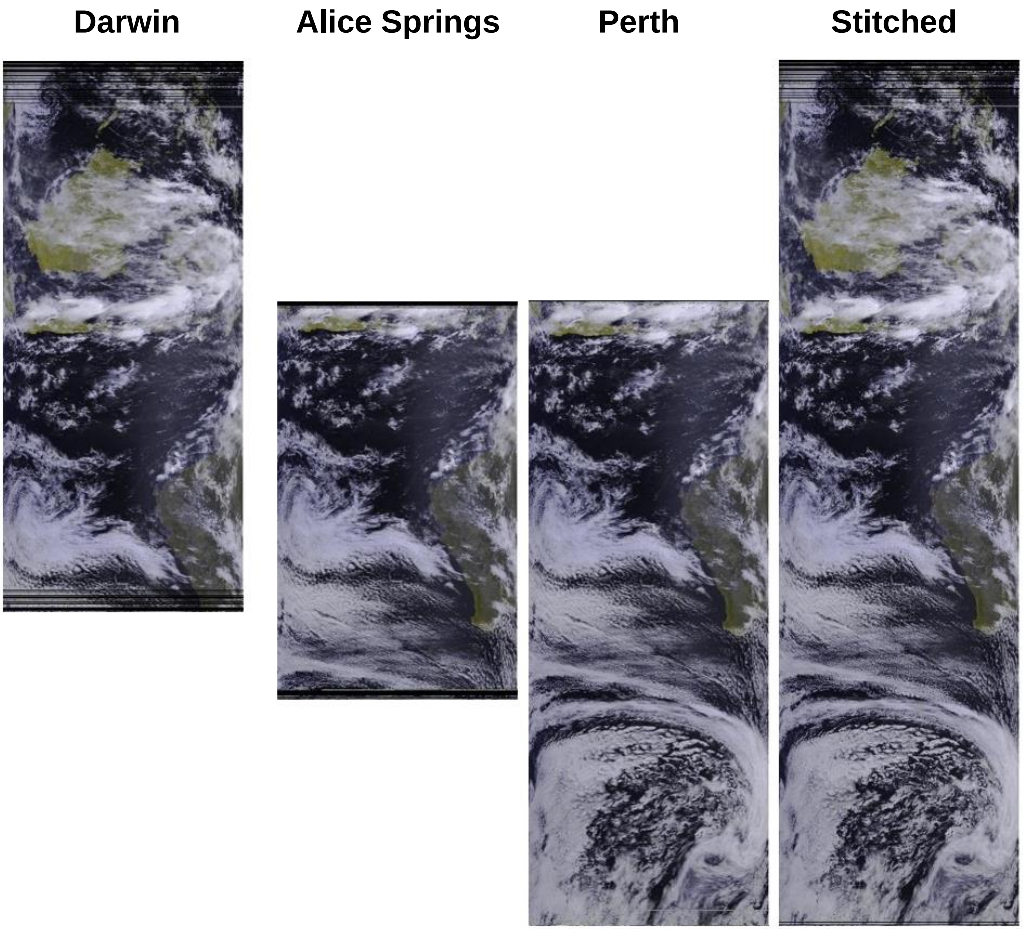


Figure 9: An example of the currently operational Australian pass stitching system using NOAA-17, data generated by the Australian National Ground Station Technical Team (www.angstt.gov.au)

11.5.3.2 Standards

The SCR mission would use a variety of best practice EO community standards for the L1/L2/L3 processing pipeline. Likely specific standards include:

- Open licencing standard: Latest version of the Creative Commons Attribution License (CC-BY)
- Metadata standards: Latest version of ISO 19131 & 19115/2 at a minimum
- File format standard: Latest version of the Cloud Optimized GeoTIFF (COG)
- Distribution standards: Latest versions of the SpatioTemporal Asset Catalog (STAC) and Open Geospatial Consortium Web Coverage Service (OGC WCS)
- Analysis Ready Data standards: Latest version of the CEOS Analysis Ready Data for Land (CARD4L) standard

11.5.3.3 Archival strategy

The SCR mission intends to be fully compliant to the Australian Archives Act 1983. This would likely be achieved with:

- Ground station telemetry and mission telemetry: Stored on dual copy spinning disk of a commercial cloud, tape storage of a commercial cloud and Geoscience Australia managed offsite tape storage. In addition, both collections would be stored within the United States Geological Survey archives.
- L1-L3 collections: Stored on dual copy spinning disk of a commercial cloud only as they can be reproduced from the ground station telemetry and mission telemetry.

11.5.3.4 Mission storage estimates

Based on the above processing pipeline overview table the following number of collections would be created by the mission:

- Level 0: 2 collections
- Level 1: 1 collection
- Level 2:
  - Option 1: 2 collections
  - Option 2: 7 collections
- Level 3:
  - Option 1: 1 collection
  - Option 2: 4 collections

Assuming the following inputs:

- Option 1: 100 metre GSD, 20km swath, 200 bands, 12 bits
- Option 2: 30 metre GSD, 20km swath, 200 bands, 12 bits

This produces the following estimates:

- New telemetry per satellite per day (as defined in section 11.3.4)
  - Option 1: 29GB
  - Option 2: 321GB
- L0 collections (Ground station telemetry and mission telemetry):
  - 20% margin added to ground station collection to account for overlap
  - Three copies of both mission and ground station archives to meet the requirements of the archives act
  - No compression on telemetry
  - Option 1: 23 TB of telemetry (GS and mission) per satellite per year
  - Option 2: 257 TB of telemetry (GS and mission) per satellite per year
- L1-L3 collections (Only one high availability copy needed due to reproducibility from telemetry):
  - Compression halves all L1-L3 storage
  - Option 1: 29GB per day x 4 collections / 2 for compression = 21 TB of products per satellite per year
  - Option 2: 321GB per day x 12 collections / 2 for compression = 703 TB of products per satellite per year
- Total (L0-L3)
  - Option 1: 44 TB per satellite per year
  - Option 2: 961 TB per satellite per year

11.6 Programmatic aspects analyses

11.6.1 Environmental qualification campaign costing

The NSTF is baselined for a cost estimate of an environmental qualification test campaign for the SCR mission. At this stage the NSTF can only provide limited shock testing support, which is strongly dependant on the size and mass of the spacecraft as well as the required shock load. Alternative test houses exist, such as VIPAC with sites in Brisbane, Sydney, Melbourne, Adelaide, and Austest Laboratories with sites in Sydney, Melbourne, Adelaide, provide shock testing services, which are capable of filling in the gap to complete local environmental qualification testing capabilities within Australia. VIPAC and Austest further provide vibration test services and may be considered as an alternative test house, should the NSTF facilities not be capable of meeting the vibration test qualification requirements. However, consideration shall be given to any cleanliness requirements related to the test space and storage space This may incur additional costs if workspace modifications are required to ensure safe handling of the spacecraft.

Tables below contain reference figures for facility access cost and a detailed estimate of the environmental test effort needed for the SCR mission.

Table 21: NSTF daily access costs

Item	ROM Cost [AUD]
NSTF facility daily rate (7 hrs)	2500
NSTF cleanroom daily rate	500
NSTF cleanroom storage day rate	50

Table 22: SCR Environmental Qualification Test campaign ROM cost

SCR Mission Environmental Qualification Tests	ROM Cost [AUD]
STM shock test (2 days) @ VIPAC or Austest	6000
STM vibration test (2 days) @ NSTF	5000
EM thermal cycling (5 days) @ NSTF	12500
EM qual shock (1 day) @ NSTF	6000
EM qual vibe (2 days) @ NSTF	5000
EM EMC test (3 days) @ NSTF	7500
EM Vacuum Thermal Balance Testing (6 days); 24/7 operation incurs factor 3 on daily rate @ NSTF	45000
FM Vacuum Thermal cycling + bakeout (12 days); 24/7 operation incurs factor 3 on daily rate @ NSTF	90000
FM acceptance vibration testing (3 days) + cleanroom storage @ NSTF	5150
EM mass properties measurements inside cleanroom (2 days) @ NSTF	6000
FM mass properties measurements inside cleanroom (2 days) @ NSTF	6000
Total ROM cost	**194150**

11.6.2 Australian-made satellite platform cost estimate

For an Australian organisation to develop a microsat spacecraft bus suitable for the SCR mission, the following costs were estimated:

Table 23: Cost estimate for Australian-made satellite bus

			Cost	QTY/FTE	Years	TOTAL
Spacecraft Bus	Labour	Project Management	AUD200k	1	3	AUD600k
		Systems Engineering	AUD200k	1	3	AUD600k
		Electrical/RF	AUD200k	4	2	AUD1,600k
		Flight Software	AUD200k	4	2	AUD1,600k
		Mechanical/AIT	AUD200k	4	2	AUD1,600k
		ADCS	AUD200k	1	2	AUD400k
		Operations	AUD200k	2	2	AUD800k
		Adminstration/Finance	AUD200k	1	3	AUD600k
		TOTAL		18	3	AUD7,800k
	Hardware, consumables, etc.	Mechanical, incl. GSE	AUD500k	1		AUD500k
		Electrical & RF, incl. GSE	AUD1,000k	1		AUD1,000k
		ADCS	AUD1,000k	1		AUD1,000k
		Operations	AUD50k	1		AUD50k
		Flight Software	AUD50k	1		AUD50k
		Assembly, Integration, Testing	AUD100k	1		AUD100k
		TOTAL				AUD2,700k
Launch estimate		Momentus				AUD3,250k
		RL electron				
		Gilmore Space				
COMBINED TOTAL						**AUD13,750k**

Labour costs were based on the estimated engineering effort to develop a microsat bus over 2 years, with Project Management, Systems Engineering, and Administration/Finance costed over 3 years. The cost of one Full-Time Equivalent (FTE) staff was approximated at AUD130k per year salary (super-annuation included), with 50% extra for over-head costs.

Other costs were based on the estimated hardware, software, consumables, materials, and expenses needed to develop a microsat bus over a 2-year period.

Launch costs included integration with launch vehicle or parent satellite and launch into the destination orbit.

11.6.3 Commercial satellite platforms

The study investigated the suitability of commercially available satellite platforms to achieve the mission objectives. This was done in two steps:

1. In the first step, publicly available information from the internet was used to identify suitable candidates and assess their ROM cost.
2. In a second step, a subset of potential vendors was contacted with a request for information (RFI) to substantiate the publicly available information.

These two steps and their results are described in further detail in the following sections.

The general conclusion from this work package is that a COTS option would reduce the overall cost for the initial SCR missions by AUD2.8M – 5.7M compared to the development of an Australian capability. As Australian maturity progresses, this difference is expected to shrink.

11.6.3.1 Assessment of publicly available information

A list of suitable candidate satellite platforms has been created based on engineering expertise and data sheet information publicly available. Suitability has been determined based on the definition of the backbox payload requirements as defined in section 11.1.1.3. For those platforms it was then tried to find publicly available information of their cost. The goal of this exercise is to derive a cost frame for the satellite bus component. Results of this exercise are summarized in the table below.

In conclusion, the satellite bus for a spacecraft in the desired mass range can be expected to cost around USD 5M based on this assessment with a substantial uncertainty and the possibility of further increased cost in case of including further mission elements in the purchase order.

Table 24: Publicly available cost information on small satellite platforms

Manu-facturer	Platform	Cost figure	No of sat's	ROM cost per satellite	Reference	Comments
RocketLab	Photon	USD 10M	1 launch incl 1 Photon		NASA Spaceflight website[63]	
Blue Canyon Technologies	X-Sat	USD 14.2M USD 99.4M	4 20	USD ~3.5M USD ~5M	Space News Feed website[64] Space News website[65]	BCT recently acquired by Raytheon Inc.
SSTL	150	USD ~238M	1	USD ~238M	Space Tech Asia website[66]	Includes training Thailand to space
	NovaSar 1	GBP 21M	1			
York Space Systems	S-Class	USD 94M	10	USD9.4M	Space News website[67]	Includes payload (data relay) and intersatellite comms.

[63] https://www.nasaspaceflight.com/2020/09/rocket-lab-debuts-photon/
[64] https://www.spacenewsfeed.com/index.php/news/4921-blue-canyon-technologies-announces-phases-2-and-3-contract-win-for-darpa-s-blackjack-program
[65] https://spacenews.com/blue-canyon-technologies-could-produce-up-to-20-satellite-buses-for-darpas-blackjack/
[66] https://www.spacetechasia.com/thailand-selects-airbus-for-theos-2-satellite-total-budget-238-million/
[67] https://spacenews.com/lockheed-martin-york-space-win-contracts-to-produce-20-satellites-for-space-development-agency/

Manu-facturer	Platform	Cost figure	No of sat's	ROM cost per satellite	Reference	Comments
	S-Class	USD 12.8M	1	USD12.8M	Space News website[68]	Tetra-3 mission for USAF.
	S-Class	USD 1.2M	1	USD1.2M	Space News website[69]	Company advertised cost for platform.
Berlin Space Technology	Kent Ridge	EUR 5M		EUR5M	Handelsblatt[70]	LEOS-50 platform Includes launch costs but this is not the platform we need (LEOS-100)
	EgyptSat-1	USD 20M			AAG.org website[71]	20M is total cost program, not just satellite. Platform is LEOS-50 BST
Ball Aerospace and Technology Corp	BCP-100 (Ball Configurable Platform)	Unknown			Satcatalog.com website[72]	e.g. Stp-Sat2, Stp-Sat3, StpSat4 heritage
Momentus	Vigoride	USD 4.8M	1	USD4.8M	Techcrunch.com website[73]	Advertised estimate prior to finished development.

[68] https://spacenews.com/york-washington-office/
[69] https://spacenews.com/u-s-military-electron-launch-first-test-for-york-satellite/
[70] https://www.handelsblatt.com/english/companies/satellite-launch-cheap-satellites-for-the-world/23508232.html?ticket=ST-8463599-WIdEfXoJgNlSazrPKr7V-ap3
[71] http://www.aag.org/galleries/gisum_files/AlRahman.pdf
[72] https://satcatalog.com/datasheet/Ball%20Aerospace%20-%20BCP-100.pdf
[73] https://techcrunch.com/2019/04/24/momentus-seeks-up-to-25-million-as-it-inks-deals-to-transport-cargo-beyond-low-earth-orbit/

11.6.3.2 RFI campaign

An RFI campaign was then started contacting some of the manufacturers listed above for more detailed information on the technical suitability of their platforms and a cost estimate. The results are shown in Table 25. Note that cost and schedule information are considered commercial in confidence and are provided in a commercial-in-confidence version of this report.

The technical consultation confirmed that for most COTS buses, the high data rates associated with the SCR mission represent a challenge that needs customisation of a COTS solution to be solved.

Table 25: RFI campaign results

Parameter	Procured element	Reference platform name	Non-compliances (to payload or mission requirements respectively)	Source
Berlin Space Technologies	Satellite bus	LEOS	• Georeferencing accuracy w/o post-processing (200-400m)	Supplier quote
	Mission	LEOS bus + Amos ELOIS Payload	• Georeferencing accuracy w/o post-processing (200-400m)	Supplier quote
Blue Canyon Technologies (Raytheon)	Satellite bus	XSat Mercury	• Downlink rate (50Mbps) • On-board storage (64GB)	Supplier quote
Eartheye/ Satellogic	Mission	-	• Swath width (30km) • Spectral bandwidth (9-24nm) • Radiometric accuracy (3%-5%) • Radiometric stability (0.5%)	Supplier quote
SSTL	Satellite bus	SSTL-MICRO	• Propulsion upgrade required	Supplier quote
York space systems	Satellite bus	S-Class	• Downlink rate (150Mbps)	Supplier quote

11.6.4 Australian technology readiness and development timeframes

A key element in providing the Australian Government with an operational capability both from a local and overseas supplier is a realistic assessment of current capabilities and an estimation of maturation timeframes. In a dedicated work package during the study the maturity of technology and team heritage was assessed for this purpose and the results are presented in the following sections.

11.6.4.1 Mission-critical technologies

The technologies to achieve the required performance for various subsystems of the SCR mission have been identified and assessed in a worldwide and Australian context. The basis for evaluation is the NASA TRL scale[74]. The results are captured in Table 26.

[74] https://sbir.gsfc.nasa.gov/sites/default/files/2020_Appendix_A.pdf

Table 26: TRL and expected development for SCR-required technologies

Element	Sub-system	Item	Performance	Option	Current TRL	Expected TRL development	Example equipment / provider	Comment
Launch	Launcher	Launcher		Worldwide	TRL 9			
				AUS	TRL 4-6	TRL 8 by 2022	Gilmour Space	According to website
Ground	Data processors	Pre-0 stitch	CCSDS conform	Worldwide	TRL 9			
				AUS	TRL 9		ANGSTT	
		L0	CCSDS conform	Worldwide	TRL 9			
				AUS	TRL 4	TRL 8 by 2023	GA development (internal or contract)	
		L1		Worldwide	TRL 9			
				AUS	TRL 6	TRL 8 by 2023	GA development (internal or contract)	
		L2		Worldwide	TRL 9			
				AUS	TRL 9			
		L3		Worldwide	TRL 9			
				AUS	TRL 9			
	Data distribution	Data distribution		Worldwide	TRL 9			
				AUS	TRL 9		GA or AusCopHub	
	Stations	Stations		Worldwide	TRL 9		GA existing assets	
				AUS	TRL 9		GA existing assets	
Space	Payload	VSWIR	General hyperspectral	Worldwide	TRL 9 TRL 4	TRL 8 by 2022	HyperScout Hyperspace	
			Full spec compatible	Worldwide	TRL 4-6		Ball CHPS spec TBC?	Spectral range TBC
				AUS	TRL 4	TRL 6 by 2021	ANU	

Element	Sub-system	Item	Performance	Option	Current TRL	Expected TRL development	Example equipment / provider	Comment
		Internal calibration unit		Worldwide	TRL 5	TRL 8 by 2022 (12-18 months)		Components are COTS, but systems are custom built
	Platform	Avionics		Worldwide	TRL 9		SSTL	
		Platform control		AUS	TRL 6-8		Inovor UNSW	Unlikely to be suitable given the mission profile (rad-hardened etc), or have sufficient storage capabilities
		Payload data handling		AUS	TRL 3		Inovor Fleet UNSW	
		Electric Propulsion	>5kNs	Worldwide	TRL 8-9 TRL 8 TRL 7-8		Enpulsion EXOtrail PhaseFour	According to website According to website According to website
				AUS	TRL 3-4	TRL 6/7 by 2022	Neumann Space	(if applicable)
		Cold gas propulsion	>5kNs	Worldwide	TRL 5 (similar systems TRL 9)	TRL 8 by 2023 (to be developed alongside platform)	Moog Vacco	According to website. System design needs to be tailored for spacecraft. (Components are COTS, but systems are custom built.)
				AUS	TRL 5	TRL 8 by 2023 (to be developed alongside platform)	Components (valves, filters, etc.): most likely from Lee Company (international company). Regulators: most likely from international company System design & integration in Australia.	(if applicable) According to website. System design needs to be tailored for spacecraft. (Components are COTS, but systems are custom built.)
		PL downlink antenna	X-band	Worldwide	TRL 9			
				AUS	TRL 3	TRL 6 by 2022	Inovor, SkyKraft, CEA, EMSolutions, UNSW	

Element	Sub-system	Item	Performance	Option	Current TRL	Expected TRL development	Example equipment / provider	Comment
		X-band Tx	>300Mbps	Worldwide	TRL 9		General Dynamics	
				AUS	TRL 2	TRL 6 by 2022 (24-36 months)	Inovor Cingulan Space	No evidence of current development.
		ADCS Components	0.02deg control accuracy	Worldwide	TRL9		Blue Canyon Sinclair Orbital Bus systems: York Space, SSTL, Photon, etc	Sizing and component integration is likely.
			ADCS	AUS	TRL 7 ADCS	TRL 8 by 2021	UNSW Inovor	Sizing changes required
			STR	AUS	TRL 4-5	TRL 8 by 2022	UNSW Inovor	
		EPS		Worldwide	9			
				AUS	2		UNSW Inovor	Existing EPS would not provide suitable power for this class.
AIT	Test facilities	TVAC		Worldwide	9			
				AUS	9		AITC	
		Shock and vibe		Worldwide	TRL 9			
				AUS	TRL 9		AusTest, VIPAC	Cleanliness needs improving
		Instrument calibration		Worldwide	TRL 9		NASA JPL, NASA Goddard, UK NPL	
				AUS	TRL 5-6	TRL 7 by 2023		Guess on development time for a trained team. No capability exists currently.

11.6.4.2 Team maturity and experience

In analogy to the TRL for hardware or software technology, another critical aspect when implementing an operational capability is the team experience and maturity. This is expressed on a similar 1 to 9 scale as technical TRL in Table 27.

From this assessment it is evident that in terms of team experience there is only a small gap between the Australian and worldwide capabilities.

Table 27: Team readiness levels for critical capabilities required for the SCR mission

Discipline	Option	Current TRL	Example organisations
FSW development	Worldwide	TRL 9	Numerous
	AUS	TRL 8	Fleet, Inovor, UNSW
System integration	Worldwide	TRL 9	Numerous
	AUS	TRL 8	Inovor, UNSW
System validation	Worldwide	TRL 9	Numerous
	AUS	TRL 8	Inovor, UNSW
Operations	Worldwide	TRL 9	Numerous
	AUS	TRL 8-9	Optus, CSIRO, Fleet, UNSW
Propulsion subsystem AIT	Worldwide	TRL 9	Numerous
	AUS	TRL ?	UNSW, UQ, DSTG, Gilmour Space
Internal calibration unit AIT	AUS	TRL 4	
ADCS Integration	Worldwide	TRL 9	Blue Canyon, Adcole Maryland
	AUS	TRL 7	Inovor, UNSW

11.6.5 Parametric cost estimation

In order to support the bottom-up costing of the SCR mission, a second approach was used to derive an estimate of the mission cost. In this approach, a parametric cost model developed by the Aerospace Corporation based on the Complexity-Based Risk Assessment (CoBRA) tool was utilised. The CoBRA analysis model uses a data set of 140 NASA led space missions over the period of two decades (1989 – 2012).[75] The complexity index of each space mission is a function of various technical and programmatic parameters of the missions such as spacecraft specifications, costs, development time, mass properties and operational status. The complexity index was calculated for all NASA led missions then graphed relative to the cost of the satellites that were successful, impaired, or suffered failure (shown in Figure 10). A regression analysis yielded an exponential relationship between the complexity index and the mission development cost. It is evident that all failed or impaired missions in the data set have been implemented with a cost below the regression curve, thus allowing to conclude that too low of a budget increases the risk of mission failure.

The application of this cost model to the Australian space context is limited. This is namely because the reference missions forming the basis for the cost model are developed, built and operated in a NASA space engineering context. A calibration attempt has therefore been made to check the cost model's performance against recent, known, Australian space missions namely UNSW Canberra Space's M2 Pathfinder and M2 missions. This calibration exercise is described in section 11.6.5.1 below.

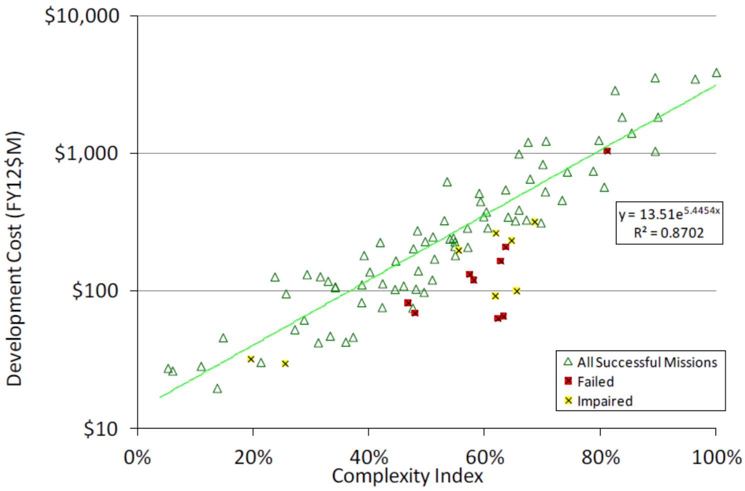


Figure 1. CoBRA Complexity and Cost Relationship

Figure 10: CoBRA parametric cost model relationship between mission complexity index and development cost

It should be noted here that the CoBRA model could not be applied as designed because this requires the knowledge of the distribution of all reference mission performance values. The research literature only provides minimum, mean and maximum values of those distributions. As a work around, a uniform distribution was therefore assumed within the range between min and max values as has also been done in similar studies[76].

The regression equation produces results in FY2012 USD. These have been converted to FY2020 AUD by first adjusting to inflation according to data from the US Bureau of Labour Statistics[77] and

[75] Yoshida, J. & Cowdin, M. & Mize, T. & Kellogg, R. & Bearden, D.. (2013). Complexity analysis of the cost effectiveness of PI-led NASA science missions. IEEE Aerospace Conference Proceedings. 1-14. 10.1109/AERO.2013.6496935.
[76] Veronica L. Foreman, Jacqueline Le Moigne and Olivier De Weck, A Survey of Cost Estimating Methodologies for Distributed Spacecraft Missions, AIAA SPACE 2016. AIAA 2016-5245. September 2016.
[77] https://www.usinflationcalculator.com/

then converted to AUD using data from the Australian Taxation Office[78]. The resulting conversion factor from FY2012 USD to FY2020 AUD is 1.75.

Employing the model as described to the SCR mission as far as currently designed and accounting for uncertainty in the various parameters yields a complexity index of 0.267 with an extreme-case uncertainty between 0.221 and 0.310. This corresponds to a mission cost estimate of AUD83M with an uncertainty range between AUD64M and AUD105M.

Table 28: SCR mission technical parameters as input to CoBRA cost model

Parameter	Value	Unit	Uncertainty range
Redundancy	20		+30 | -10
Orbit	2		+2 | -2
Propulsion Type	5		+5 | -3
Design Life	24	months	+60 months | -24 months
Launch Margin	2	months	+2 months | -2 months
Solar Cell Type	2		+2 | -2
Pointing Knowledge	0.016667	deg	+0.042 deg | -0.017 deg
Battery Capacity	100	Wh	+120 Wh | -100 Wh
No. of Articulated Structures	1		+1 | -1
Thermal Type	0		+0 | -0
ADCS Type	3 axis stabilised, star tracker		
Data Volume	116	GB/day	+348 GB/day | -29 GB/day
Satellite Mass	35	kg	+57.6 kg | -27 kg
No. of payloads	2		+4 | -1
Radiation	20	krad	+60 krad | -12 krad
Delta-V	100	m/s	+200 m/s | -0 m/s
Data Storage Capacity	320	GB	+320 GB | -128 GB
PL mass	15	kg	+18 kg | -12 kg
Launch Mass	38.5	kg	+69.696 kg | -29.7 kg
Bus Dry Mass	20	kg	+30 kg | -15 kg
PL Data Rate	100000	kbps	+200000 kbps | -10000 kbps
S/C Heritage	40		+60 | -20
Orbit Average Power	43.225	W	+77.805 W | -15.12875 W
Battery Type	Li ion		+4 | -4
No. of deployed Struct	4		+6 | -2
Solar Array Config	Deployed fix		
Pointing Accuracy	0.016667	deg	+0.042 deg | -0.0017 deg
Uplink Data Rate	1	kbps	+11 kbps | -0.1 kbps
Flight SW reuse rate	50	%	+90 | -0
No. of thrusters	1		+4 | -0
Structure Material	Aluminium		
EoL Power	123.5	W	+185.25 W | -61.75 W
BoL Power	130	W	+195 W | -65 W
PL avg Power	40	W	+52 W | -28 W
Foreign Partnership	Payload		

[78] https://www.ato.gov.au/Tax-professionals/TP/Calendar-year-ending-31-December-2020/

Parameter	Value	Unit	Uncertainty range
PL peak Power	100	W	+120 W | -50 W
Slew Rate	0.060683	deg/s	+0.121 deg/s | -0.061 deg/s

11.6.5.1 Calibration of cost model to Australian context

To provide a calibration reference for the CoBRA cost model applied to an Australian satellite mission, the results of the cost model have been compared to actual mission costs of two Australian missions. While this is not a scientifically sound method to derive an error value between the cost model results and an expected SCR mission cost, it does enable an assessment of the order of magnitude of the obtained cost figures.

The result of this exercise is summarized in Table 29. Details can be found in the commercial-in-confidence version of this report.The table shows the ratios between parametric and actual cost for the M2 Pathfinder and M2 missions as developed, built, and operated by UNSW Canberra Space. The values are significantly different with the uncertainty ranges not overlapping.

Table 29: Cost ratio between CoBRA model and actuals for 2 recent space missions

	M2 Pathfinder	M2
CoBRA cost / actual cost	10.5	2.87
Uncertainty range	7.5 – 16	2.2 – 4.4

This may be explained by the mission context of the M2 Pathfinder mission. It was implemented to de-risk many of the M2 subsystems and could thus benefit from some NRE efforts that had been previously performed and budgeted under the M2 mission cost. This way it was possible to implement the M2 Pathfinder mission for a relatively low actual cost. This allows the conclusion that the presented ratio for the M2 Pathfinder mission is likely too high.

A realistic figure for the ratio to transform CoBRA cost estimates to the Australian space context is likely to be found in the range between 2.5 and 5.

Applying this value to the parametric cost estimate of the SCR mission (AUD83M) yields an adjusted Australian-context cost of AUD16.6M to AUD33.2M. This is in very good agreement with the bottom-up cost estimate as presented in chapter 10.1.

12 Recommendations and open points

The study makes the following recommendations:

1. The tendering process for the next steps of the SCR pathfinder missions should be initiated as rapidly as possible to have a realistic chance of operating the mission in cooperation with NASA's CLARREO Pathfinder mission.
2. The following satellite technologies can be simultaneously de-risked and developed to provide internationally competitive, Australian satellite subsystems because they currently do not exist as required on the commercial market:
    a. A hyperspectral instrument meeting all observation requirements as identified including the facilities to assemble and integrate it.
        i. This work package requires a consolidation of the observation requirements in particular the definition of any remaining open parameters such as the required SNR as a function of wavelength.
    b. A micro-satellite on-board calibration subsystem for a hyperspectral payload to achieve radiometric stability of 0.2% over 30 days.
    c. A high-data rate payload data handling subsystem for micro-satellites capable of simultaneously reading and writing hyperspectral data streams.
    d. An X-band transmitter and antenna to achieve >250Mbps downlink data rate for a micro-satellite.
3. A mission analysis exercise to identify optimal orbits to maximise cross-calibration opportunities is required and can be performed independently of any other activities listed here. Having its results as an input to subsequent design phases would significantly reduce schedule risk.
4. Explore the viability of a new ground station site in Antarctica, including undersea cable, as it would allow complexity on the spacecraft communications system to be reduced. This site would be particularly relevant if Option B was pursued.
5. UNSW Canberra Space assesses the SCR mission is ready for phase B mission development analysis following completion of all open points and questions (Section 12.1) and selection of the preferred option: to pursue a satellite cross-calibration series (Option A) or transition to a multimission hyperspectral smallsat series following launches three and four (Option B).
6. A phase B study could in parallel mature relevant Australian-built satellite subsystems and thus further reduce the risk of the Australian industry content implementation pathway:
    a. A thermal control concept to ensure the stable operating environment for the hyperspectral payload to achieve the required radiometric stability.
    b. An ADCS subsystem capable of controlling the satellite as required
    c. An electric power subsystem providing the required power to the satellite

12.1 Open points and questions

This study is pre-decisional and wants to explore mission feasibility only hence it has not been labelled in NASA mission development phases. The following list identifies open questions that have not been answered as part of the study and require further analyses in subsequent design phases, if all of these items were fully explored this mission may be suitable for NASA phase B space mission development activities following adequate peer review:

- Further describing the observation requirements in particular the definition of SNR as a function of wavelength
- Mission analysis to identify suitable/optimised orbits for non-trailing SCR
- Achievable levels of on-board data compression
- Definition of cross-calibration data format to ensure usability for collaborating users
- Payload data downlink architecture trade-off
- Program/project technical management plans

13 List of acronyms and abbreviations

Table 30: Abbreviations and acronyms

Abbreviation	Description / meaning
18 SPCS	18th Space Control Squadron
ACT	Australian Capital Territory
ADCS	Attitude determination and control subsystem
AGO	Australian Geospatial-Intelligence Organisation
AIT	Assembly, Integration, and Test
AIT	Assembly, integration and test
AITC	Advanced Instrumentation Technology Centre
ANCDF	Australian National Concurrent Design Facility
ANGSTT	Australian National Ground Segment Technical Team (www.angstt.gov.au)
ANU	Australian National University
APEC	Asia-Pacific Economic Cooperation
ARD	Analysis-ready data
ASA/The Agency	Australian Space Agency
ASD	Australian Signals Directorate
ASDC	Australian Space Discovery Centre
AUD	Australian Dollar
AUS	Australian
AusCopHub	Copernicus Australasia Regional Data Hub (www.copernicus.gov.au)
BCT	Blue Canyon Technologies
BRMM	Buccaneer Risk Mitigation Mission
BST	Berlin Space Technologies
Cal/Val	Calibration and validation
CARD4L	CEOS Analysis Ready Data for Land
CC BY	Creative Commons, Attribution
CCSDS	Consultative Committee for Space Data Systems
CDF	Concurrent Design Facility
CEOS	Committee on Earth Observation Satellites
CLARREO	Climate Absolute Radiance and Refractivity Observatory
CNES	Centre national d’études spatiales
CoBRA	Complexity-based risk assessment
COG	Cloud Optimized GeoTIFF
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
DSTG	Defence Science and Technology Group
DV	Delta-V (velocity increment)
EC	European Commission
EHS	Earth Horizon sensor
EM	Engineering Model
EMC	Electromagnetic compatibility

Abbreviation	Description / meaning
EO	Earth Observation
EPS	Electrical Power Subsystem
EQM	Engineering qualification model
ESA	European Space Agency
ESD	Electro-Static Discharge
FM	Flight Model
FOC	Full Operational Capability
FTE	Full-Time Equivalent
FWHM	Full-width half maximum
FY	Fiscal Year
G	Goal (for requirements)
GA	Geoscience Australia
GDP	Gross domestic product
GLAMR	Goddard Laser for Absolute Measurement of Radiance
GPS	Global Positioning System
GS	Ground station or ground segment
GSD	Ground sampling distance
GSE	Ground support equipment
HIS	Hyperspectral imager
Isp	Specific impulse
ITAR	International traffic in arms
KO	Kick-off
LED	Light emitting diode
LEO	Low Earth Orbit
LEOP	Launch and Early Orbit Phase
LGN	Landsat Ground Network
LSP	Launch service provider
LV	Launch Vehicle
MOC	Mission Operations Centre
MOI	Moments of inertia
N/A	Not applicable
NASA	National Aeronautics and Space Administration
NICSAT	National Intelligence Community Satellite
NPL	National Physical Laboratory
NSTF	National Space Test Facility
OBC	On-board computer
OGC WCS	Open Geospatial Consortium Web Coverage Service
PDR	Preliminary Design Review
PF	Pathfinder
PFM	Proto-flight model
PICS	Pseudo invariant calibration sites
PL	Payload
RAAN	Right ascension of the ascending node
RF	Radio frequency
RFI	Request for information
ROM	Rough order of magnitude

Abbreviation	Description / meaning
S/C	Spacecraft
SCR	Satellite Cross-Calibration Radiometer
SM	Structure model
SNR	Signal-to-noise ration
SSO	Sun-synchronous orbit
STAC	SpatioTemporal Asset Catalogs
STEM	Science, technology and maths
STM	Structure and thermal model
SWIR	Short-Wave Infrared
T	Threshold (for requirements)
TBC	To be confirmed
TBD	To be determined
TIR	Thermal Infrared
TM	Thermal model
TOA	Top of atmosphere
TRL	Technology Readiness Level
TRUTHS	Traceable Radiometry Underpinning Terrestrial- and Helio- Studies
TT&C	Telemetry, Tracking, and Command
UK	United Kingdom
UNSW	University of New South Wales
US	United States
USAF	US Air Force
USD	US Dollar
USGS	United States Geological Survey
VNIR	Visible and Near-Infrared
VSSEC	Victorian Space Science Education Centre
VSWIR	Visible and short-wave infrared
w/o	without

14 Appendix A: Study participants

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

Table 31: List of personnel involved in the study

Organisation	Person	Role / contacted for
AGO	Mathew Withheld	Study participant link to defence (DEF799)
ANU / AITC	Rob Sharp	Optical payload specialist
Australian Space Agency	Aude Vignelles	Programmatic guidance
	Reece Biddiscombe Arvind Ramana	
	Kerrie Dougherty	Education/outreach expert
Berlin Space Technologies	Abdel Ismail Tom Segert	Business development Satellite bus provider
Blue Canyon Technologies	Ben Anderson	Satellite bus provider
CSIRO	Alex Held	AquaWatch programme
Eartheye	Nigel Conolly Shankar Sivaprakasam	EO imagery provider
Geoscience Australia	Maree Wilson	Project Sponsor
	David Hudson Jonathon Ross	Customer point of contact
	Medhavy Thankappan	Cal/Val expert
	Vincent Rooke Roger Melton	Ground station experts
	Leo Lymburner Chris Penning Emma Luke	Earth observation experts
RocketLab New Zealand	Sandy Tirtey	Launch / satellite bus provider
SSTL	Alex da Silva Curiel Victoria Irwin Clive Oates	Satellite bus provider
Syrlinks	Guillaume Choain	Spacecraft communications subsystems provider
UNSW Canberra Space	Denis Naughton Jai Vennik Igor Dimitrijevic Edwin Peters Anthony Kremor Sam Boland Russell Boyce Jan-Christian Meyer Courtney Bright Philippe Laniakea Vraj Patel	Mission design and domain expertise
York Space Systems	Melanie Preisser Benjamin Kron Mike Lajczok	Business development and technical support Satellite bus provider

15 Appendix B: Commercial-in-Confidence information and quotes

Information in this annex is considered commercial in confidence and was provided to Geoscience Australia and the Australian Space Agency only.

UNSW CANBERRA | Space

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

space.unsw.adfa.edu.au

@UNSWCanberra
@UNSWCanberra
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