AQUAWATCH

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Preliminary Concept Study for the Satellite Segment of AquaWatch Australia

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Executive Brief

This report presents the findings of a preliminary concept study undertaken by the University of New South Wales (UNSW) Canberra Space at the Australian National Concurrent Design Facility (ANCDF), for the AquaWatch Australia Phase 0 (i.e. pre-Phase A) project under the leadership of Commonwealth Scientific Industrial Research Organisation (CSIRO) and SmartSat CRC. The study, held in February 2021, was the 14th conducted at the ANCDF and it involved 23 people from 9 organisations.

- CSIRO and the Smartsat CRC have partnered on AquaWatch Australia (hereinafter known as "AquaWatch"), a mission to build an integrated, operational Earth Observation (EO) system for monitoring and managing Australia's inland and coastal water bodies.

- It is expected that the space-based earth observation component of AquaWatch will be a valuable piece of Australian operational, sovereign space infrastructure, supporting sustainable economic growth in a range of industries, environmental management and safe, healthy communities.

- The AquaWatch Phase 0 project sought to develop the AquaWatch concept and prove the feasibility of the system.

- Within AquaWatch Phase 0, further 'End User Consultation' has been performed, to establish the business case and to catalogue end-user needs and wants. This led to the creation of initial system requirements; an input to the Concurrent Design Facility (CDF) study covered in this report.

- The preliminary CDF study provided an understanding of the issues around the AquaWatch programme's space segment; namely the development of a practical system design that meets the user requirements, and an initial cost estimate informing its business case. Several AquaWatch instrument payload concepts were explored.

- The selection of a final technical solution for the operational AquaWatch satellites will require further detailed analyses of the mission. We were able to identify a system design that addresses those requirements and is feasible to construct, commission and operate.

- Further analysis is needed, particularly in terms of achieving the challenging revisit times set by the user needs, and the trade-off between spatial resolution and associated signal to noise performance of the sensor, given the known performance of available components.

- The analysis conducted in the course of the CDF should be considered preliminary, as a means to understand the basic payload and operational needs for the mission space segment, and to analyse trade-offs between water quality monitoring user needs, space engineering practicalities, and associated costs.

- The construction of the whole AquaWatch system would leverage mainly existing and emerging technologies (domestic and overseas), including in-situ sensors and space capabilities. It would also require some targeted R&D activities, particularly around customised satellite imaging systems. A high proportion of locally-developed sub-systems is expected.

- The construction of the AquaWatch space segment would also support growth of domestic industrial capability, and a high degree of reuse, in domestically designed and constructed "small" (up to 200kg class) satellites.

- What were called here "Breakthrough" level requirements lead to a technically challenging instrument design that in turn has important implications for the satellite design and locally sourced components.

- However, several opportunities exist to de-risk the AquaWatch mission and raise local TRL levels through specific, targeted 'pathfinder' missions, that are well within current technical capabilities of the Australian space industry. Aside from pathfinders, the design supports a methodical System Engineering approach with a staged roll out. Software can be developed in an iterative/evolutionary/agile way. The modular design means that we have easily separable work packages.

- The study has developed one mission concept in detail (mission concept A) and two alternatives, with lower performance and lower cost (mission concepts B and C).

- Mission cost estimates for concept A indicate AUD 132M for one satellite, which includes, design, manufacture, integration and test, launch, operations and decommissioning.

- Second and subsequent satellites of similar performance are expected to cost around AUD 47M including launch etc. Additional satellites will greatly improve the revisit time and overall benefits of the system.

- There is the potential for cost and schedule savings by considering design reuse or economy of scale implementations with other Australian Earth observation proposals currently under development.

- The economic, environmental, and societal benefits of operating AquaWatch are expected to be very large. Parallel, AquaWatch activities in Market Analysis and End User Consultation are being undertaken to quantify the expected impacts of AquaWatch.

- We acknowledge the active participation and contributions to this study by domain experts from: UNSW Space, CSIRO, University of Queensland, Curtin University, SmartSat CRC, Australian National University, Geoscience Australia, Defence Science and Technology Group, and the Australian Space Agency (names listed in Appendix B).

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1 Executive summary

1.1 Introduction

This study was conducted by the UNSW Canberra Space, in collaboration with, and on behalf of CSIRO and SmartSat CRC, with additional expert participation by Curtin University, SatDek, Australian National University (ANU), University of Queensland, Defence Science and Technology Group and the Australian Space Agency (ASA). It applied a concurrent engineering methodology, closely aligned to the National Aeronautics and Space Administration (NASA) systems engineering approach, to derive a space mission feasibility assessment and programmatic cost estimation. The study involved 23 people from 9 organisations.

The results of this work show that the AquaWatch System is practical and feasible to build and will inform the Australian Government Satellite Earth Observation Roadmap ("the Roadmap") being developed by the ASA, the Bureau of Meteorology (BoM), CSIRO, the Department of Defence and Geoscience Australia (GA), in close partnership with the Australian Earth Observation community.

1.2 Overview of AquaWatch

The 'AquaWatch Australia' Mission was established by CSIRO in 2020 as a cross-organisational program and a new partnership with the SmartSat CRC. The aim of the AquaWatch mission is to develop and roll out a nationally integrated water quality monitoring system. Water is a vital resource – and water security is under increasing pressure from human impacts, climate change and water quality threats. The need for accurate, timely, consistent large-scale data for monitoring the health and cleanliness of our coastal and inland waters is critical.

The AquaWatch mission is a partnership between the CSIRO and the Smartsat CRC with support from government agencies: GA, the BoM, and the ASA, as well as industry and the research sector.

The mission is seeking to lead delivery of a nationally co-ordinated approach to a balanced and transparent pipeline of technology-led activities that seek to address environmental, social and economic challenges through the design, build, testing and roll-out of advanced space technology to deliver Earth Observation data.

Within its 'Phase 0' project, the AquaWatch mission is undertaking concept development and feasibility analysis, to examine the opportunity to build an advanced Earth Observation infrastructure system, designed and purpose-built to meet the specific needs of Australian coastal and inland water quality mapping, monitoring and support predictive analytics.

The overall space-segment of the mission concept involves the manufacture and launch of a number of hyperspectral imaging satellites that deliver real-time satellite observations, augmented by a network of ground-based sensors, to deliver real-time data for monitoring and managing our valuable freshwater resources, and our coastal environments. AquaWatch will provide a world-first, custom water quality monitoring-focused satellite Earth observation mission/constellation with a global footprint.

1.3 The AquaWatch Space Segment

The mission seeks to engage with local industry to scope, design, build and launch an advanced ground-to-space water quality monitoring capability. In this capacity, the AquaWatch system will support the growth of Australia's upstream advanced manufacturing and high–tech industry capabilities, driving the development of locally built Earth Observation satellites.

The space segment will include a constellation of bespoke Earth Observation satellites (small, sub-200 kg satellite class) featuring hyperspectral imaging cameras. These cameras provide high ground resolution and dynamic range but are unique in being able to provide precise and detailed spectral information, enabling the detection of water body content and chemistry.

The commissioning of AquaWatch is expected to also catalyse growth for Australia's environmental monitoring and Earth Observation (EO) industries. The AquaWatch system will also supply new high-quality data that would help grow the down-stream data, value-adding geospatial industry, as it will require a comprehensive data analytics platform, programs and data value-adding jobs that integrate prediction modelling, data analysis and environmental monitoring. This water quality and water health data will provide the necessary transparency required for water agencies and utilities that are the stewards of this critical resource.

Data scarcity is a critical issue facing effective water quality management due to lack of sovereign satellite assets, and limited number of in-situ observations across Australia - being logistically challenged and expensive to build, robust enough to survive extreme weather and climatic conditions, and historically have been built to measure water quantity.

AquaWatch will aim to compliment and contribute to existing national water resource accounting programs, and provide precise, real-time, decision-ready information on the quality of water for Australia's waterways, reservoirs, and coastal environments, and its variations over time and space, including degraded water quality, ecological integrity and freshwater resiliency in a changing climate.

This data will provide early warning of water quality threats, predicting and mitigating the effect of local and global environmental events (bushfires, storms, harmful algal blooms) and industrial stressors (pollutants, infrastructure assessment, management & remediation) and monitoring and analysing the freshwater and marine eco-systems (supporting sustainable growth in primary industries) to deliver tangible widespread societal, economic and environmental benefits to Australians.

AquaWatch would also represent Australia's contribution to **GEO-AQUAWATCH**[1] whose mission is to "develop and build the global capacity and utility of Earth Observation-derived water quality data, products and information to support water resources management and decision making".

1.4 CDF Study

This preliminary study was conducted at the Australian National Concurrent Design Facility (ANCDF) and is a technical output of the 'AquaWatch Phase-0' project that has also included End User Consultation to catalogue needs and wants across a broad cross-section of potential end-user communities:

- Primary Industries
  - Agriculture
  - Aquaculture
  - Mining
- Planning and Environment
  - Federal government departments
  - State government departments
  - Local governments
  - NGOs such as the MDBA, GRBF
- Water Utilities
  - Water suppliers from across Australia
  - Hydroelectric power suppliers
- Water Science
  - CSIRO
  - The BoM

This information was also used as part of an initial market analysis & impact assessment for AquaWatch, and the creation of a detailed and maintainable business case (summarising and quantifying economic, environmental, and societal benefits) for investment options analysis.

This consultation process has also provided initial AquaWatch System Requirements that guided the subsequent development of several space-segment options for an operational AquaWatch mission within this CDF study. This study focuses on developing the Earth Observation system of the AquaWatch mission: the

[1] https://www.geoaquawatch.org/

space segment including Earth Observation satellites with hyperspectral cameras, and the ground segment which includes stations for data downlink and Telemetry, Track & Command (TT&C).

The results of this work will inform the Australian Government Satellite Earth Observation from Space Technology Roadmap being developed by the ASA, the BoM, CSIRO, the Department of Defence, and GA in close partnership with the Australian Earth observation community.

1.5 Applicable Documents

1. CEOS (2018): Dekker, A.G & Pinnel, N. (Eds) Feasibility Study for an Aquatic Ecosystem Earth Observing System. CEOS Report, CSIRO, Canberra, Australia

2. Dekker, A.G. and MacLeod, A. (2021) AquaWatch Australia – Phase 0 End-user Consultation. Round 1, CSIRO Technical Report, Canberra, Australia.

3. IOCCG (2018) Greb, S, Dekker, A.G. and Binding, C. (eds) Earth Observations in Support of Global Water Quality Monitoring., IOCCG Report Series, No. 17, International Ocean Colour Coordinating Group, Dartmouth, Canada

4. Malthus, T.J., Dekker, A.G., Xiubin Q. and MacLeod, A. (2021) In Situ Sensor Networks - Strategy Green Paper. AquaWatch Project Report. CSIRO, Canberra, Australia.

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4 Study Context

The preliminary CDF activity described in this report is a part of the AquaWatchPhase-0 project, which involves the Concept Development and Feasibility Study for the AquaWatch mission.

Through this preliminary CDF activity we aimed to draw on the available expertise and rapidly iterate through a range of design options and decisions for the AquaWatch Australia system using a Systems Engineering approach as summarised in Figure 1. The goal was to match the requirements of the AquaWatch system (derived from a process of End User Consultation and drawing from existing studies) to a System Architecture that addresses those requirements while being feasible to build.

Although the system requirements and design are not mature or stable, this first pass at reconciling them has shown an ability to "close the loop" with regards to matching wants/needs to a system that is feasible. It is also a basis from which the system requirements and system design can evolve and be refined.

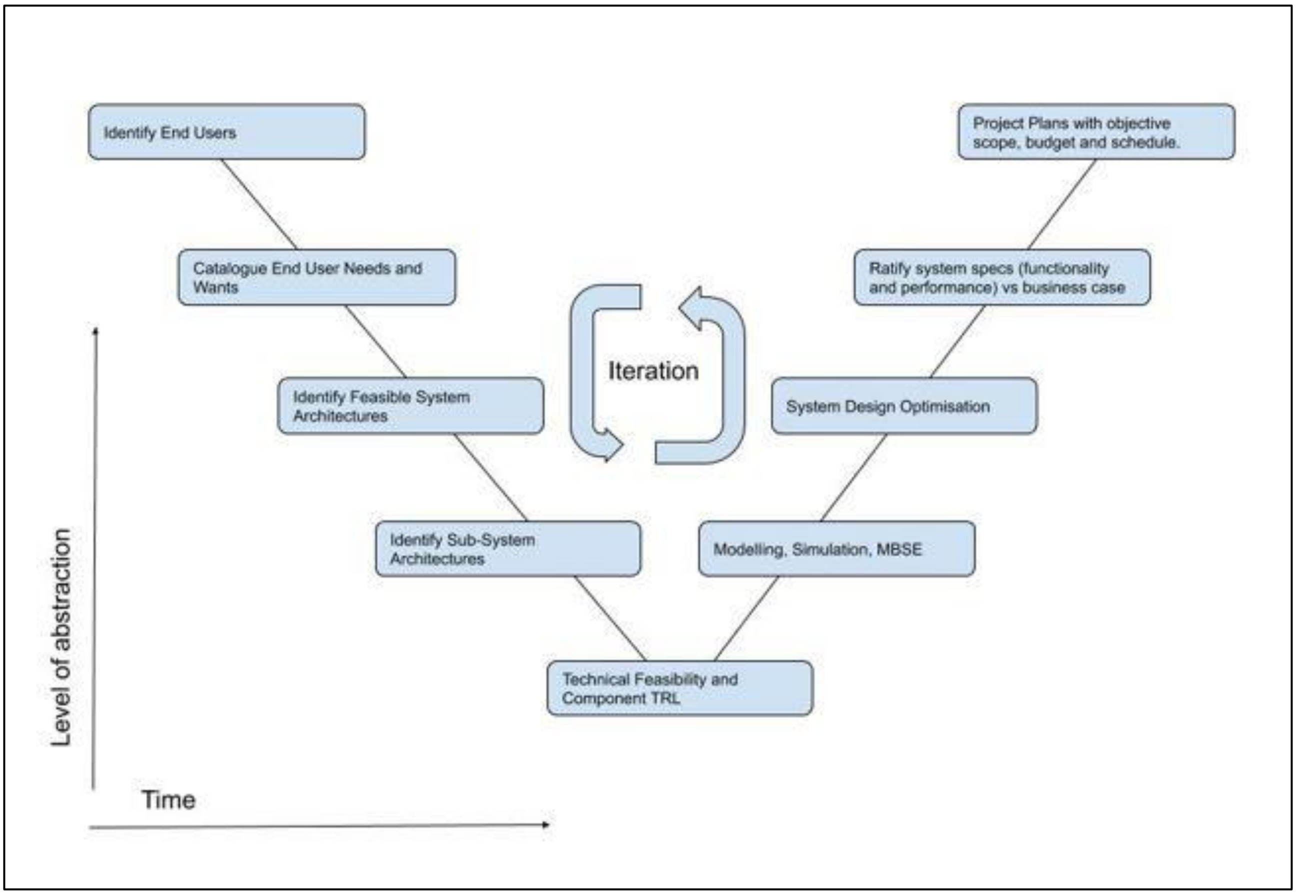

Figure 1: System Engineering V-Model applied to AquaWatchPhase-0

The study and its report also contribute to the development of the Australian Government Satellite Earth Observation from Space Technology Roadmap; a series of reports are being written that elaborate on preliminary technical design studies of various satellite systems. At UNSW Canberra Space's ANCDF, three studies have been undertaken to support the roadmap process:

- AquaWatch Phase 0 study
- Satellite Cross-Calibration Radiometer (SCR) Pre-Phase A study *(incl. potential to support partner programs)*
- Meteorology & Disasters Pre-Phase A study

A system engineering approach and a project life-cycle development methodology similar to the NASA Systems Engineering Program/Project Life Cycle has been followed. In general terms the overall purpose and the outcomes of the study are described in Table 1.[2]

Table 1: NASA definition of space mission Pre-Phase A (Phase 0)

Pre-Phase A (Phase 0)	**Concept Studies**
Purpose	The purpose of Pre-Phase A is to produce a broad spectrum of ideas and alternatives for missions from which new programs/projects can be selected. During Pre-Phase A, a study or proposal team analyses a broad range of mission concepts that can fall within technical, cost, and schedule constraints and that contribute to program and Mission Directorate goals and objectives. Pre-Phase A effort could include focused examinations on high-risk or high technology development areas. These advanced studies, along with interactions with customers and other potential stakeholders, help the team to identify promising mission concept(s).
Typical outcomes	- Review/identify any initial customer requirements or scope of work at Mission, Science and Top-level system levels - Identify and involve users and other stakeholders - Identify key stakeholders for each phase of the life cycle - Capture and baseline expectations as Needs, Goals, and Objectives - Define measures of effectiveness - Develop and baseline the Concept of Operations - Identify and perform trade-offs and analyses of alternatives - Perform preliminary evaluations of possible missions - Identify risk classification - Identify initial technical risks

This CDF study focuses only on the Earth Observation system of the AquaWatch mission: the space segment which includes the spacecraft and imaging payload, and the ground segment which includes the receiver stations. It does not include the mission operations centre elements or the launch elements.

Our approach to development of the satellite requirements can be understood from the diagram in Figure 2. The background research and end user consultations described in section 6 provided key inputs into the process. The terms breakthrough and target can be interpreted as those requirements that are mandatory and that are aspirational goals. They serve to provide potential suppliers the level of performance that is required and guide future funding efforts that may be needed by vendors to develop their capability to develop an AquaWatch system.

[2] https://www.nasa.gov/seh/3-project-life-cycl

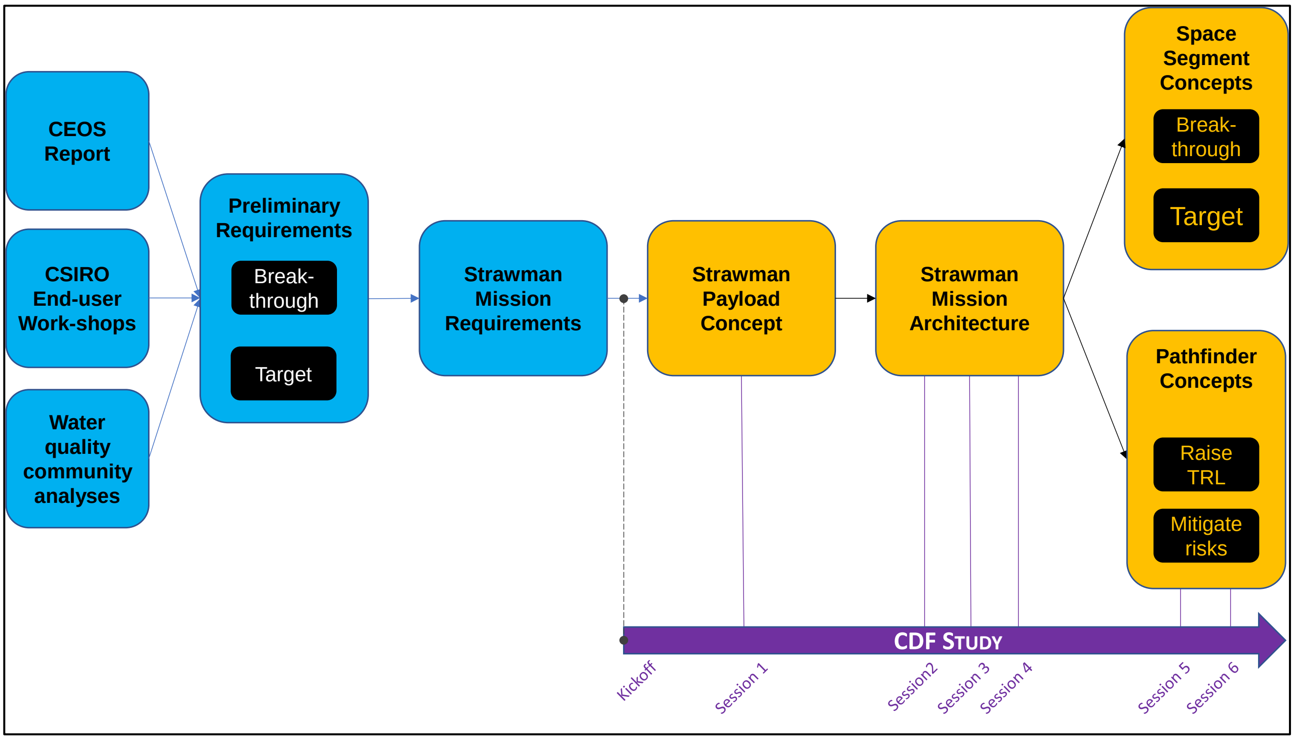

Figure 2: Methodology for development of satellite requirements (CEOS report = CEOS (2018)).

The CDF study was conducted over several weeks and contained eight 4-hour sessions. The objectives of each session are described in Table 2.

Table 2: Overview of second AquaWatch CDF study

Session	Topics Covered
Session 1 – Overview of AquaWatch Australia	– Introductions – Mission introduction – Project overview – ANCDF introduction and study overview – CEOS report summary presentation
Session 2 – Preliminary AquaWatch Australia Requirements	– User requirements presentation(s) – Overview of current and planned related missions – Overview of instruments on current and planned related missions – Identify mission requirements options, select baseline for CDF study
Session 3 – Mission Architecture Trade-offs	– User/Mission requirements recap – Mission trade-offs identification and discussion – Identification of actions for offline work
Session 4 – AquaWatch Australia Space Segment	– Recap and update of trade-off options – Discussion of instrument concept (dedicated vs. gap-filler) – Discussion of sensor technology options – Discussion of on-board processing capability incl assessment of TRL – Discussion of constellation options

Session 5 – AquaWatch Australia Ground Segment	– Discussion of ground segment including – In-situ sensors and impacts on space segment – Ground station locations / network – Data processing and dissemination – Discussion of data calibration approach and model – Discussion of mission development approach – Selection of preliminary mission concept baseline
Session 6 – Business Case and Risks	– Recap of mission concept baseline – Qualitative mission cost estimation through analogy – Business case discussion – Discussion of procurement strategy options – Mission risk assessment – Identification of actions for offline work
Session 7 – Concept and Requirements Iteration	– Mission requirements consolidation – Alternative mission concept discussions and analysis – Other items identified during the study – Identification of actions for the final presentation
Session 8 – AquaWatch Australia Concept Development Roadmap	– Any open action items – Internal conclusions – Identification of action items for the study team beyond this CDF study – Preliminary plan for second CDF study at the beginning of 2021 – Final presentation (can be opened to a wider audience if desired)

5 User Needs and Technical Requirements

Establishing the technical requirements of the satellite and sensor networks that will comprise AquaWatch requires two key components: first, an understanding of end user needs, water management authorities, aquaculture industry, and many other stakeholders; and second, a thorough understanding of the science that links remote sensing data to actionable water quality information.

5.1 Inputs to the CDF

In this section we outline our approach to development of the satellite requirements based on expert input related to these components.

5.1.1 AquaWatch user requirement resources

The CDF study took as input a set of preliminary performance requirements and user preferences for the AquaWatch system. These requirements are derived from two main sources:

1. The Committee on Earth Observation Satellites (CEOS) report titled Feasibility Study for an Aquatic Ecosystem Earth Observing System (2018) provided a broad wish-list from the water quality research community of AquaWatch space segment requirements. The report also includes international contributions. The spatial, spectral, radiometric and temporal resolution (i.e. revisit time) performance requirements were consolidated with respect to the end-user functions that could be performed and presented at the start of this CDF study.

2. AquaWatch Phase 0 End User Consultation Round 1 Report (2021) describes End users' requirements for satellite services and were conceptually divided among three domains:
    - *Water quality*, which users expect to be primarily determined by hyperspectral imaging in the Visible and NIR.
    - *Water temperature*, as estimated by thermal imaging.
    - *Water quantity*, as estimated by pixel classification and estimation of area covered or partly covered by water, as determined by high spatial resolution imagery.

The requirements are summarised in tables below and are based on feedback from many users that were collected during a series of CSIRO sponsored workshops. The result of this process is two levels of mission requirements as shown in the above diagram.

5.1.2 Cataloguing End User Needs and Wants

The AquaWatch Phase 0 End User Consultation aimed to:

a. Catalogue the greatest water quality challenges of our potential end users.
b. Interpret their needs and wants.
c. Identify issues and opportunities.
d. Understand the impact of addressing these.

This consultation focused on current activities and issues. Also, it addressed Australian end users only. As part of the consultation process, we ran a series of workshops with end users from:

- Planning and environment (including the BoM, GA, along with a range of state departments and peak bodies);
- Water utilities (including water suppliers and individuals from the hydro-electric industry).
- Primary Industries (broad range of users from Agriculture, Aquaculture and Mining).
- Water Sciences (specialists in water quality research from academia, NGOs and CSIRO).

Within each workshop we aimed to get representation from each state and each major industry (within the relevant category). The workshops included facilitated break-out group discussions around a generalised set of questions. The workshops generated a lot of information, and the results of these workshops, including traceability to requirements listed below are contained in the “AquaWatch End User Consultation Report”, *available upon request.*

5.2 End-user imaging requirements

The following sections summarise the results of end-user solicited image product and mission requirements and information consolidated in the CEOS Report and provides an initial set of system requirements for AquaWatch

5.2.1 Hyperspectral imaging

End users’ requirements that could be met by a multispectral or hyperspectral imaging payload distributed in a satellite constellation ‘are listed in Table 3. Several key water quality parameters can be determined by spectral imaging from space platforms requiring optical bands ranging from 360 to 1000 nm (VIS-NIR), and with improved results using bands in the 1000-1400nm (SWIR) range.

Legend (from consolidated responses from 3 breakout groups in each workshop):

- *Black = mentioned once or twice*
- *Blue = mentioned often (3 to 4 times)*
- *Red = all end users wanted this*

Table 3: AquaWatch end user requirements/goals for hyperspectral imaging

Parameter/Requirement	Breakthrough	Target
Ground resolution	30m 10m	10 m 20 m
Orbital revisit time, all water bodies in Australia	5 Days Less for Reporting of trends, State-of-the-Environment	< 5 Days
Compounds of interest: directly observable	– Cyanobacterial pigments (CPC, CPE) – Chlorophyll – Algal blooms – CDOM – TSS, Turbidity	- Highest possible sensitivity to Algal blooms (early warning, fate, breakdown etc)
	– Effects of dredging – Aquatic Macrophyte extent – Seagrass: species and extent – K_d for seagrass restoration	Phytoplankton functional types & species
EO Satellite: Compounds/Spectra of interest by proxy	Algal toxins; Pathogens. Overland flows: Blackwater events	
	Fish kills; Coral reef health	
EO Satellite: Spectral resolution	8 nm	5 nm

Data Analytics: Post-Processing and processing pipeline functions	ARD + IRD (Analysis Ready Data and Interpretation Ready Data)	Pay attention to provenance and chain-of-custody for legal use.
	Easy to use platform-lots of visual tools for end user/stakeholder engagement.	Coupled catchment, hydrodynamical, biogeochemical and algal growth model
	Data assimilation: in situ, remote sensing, and Water Quality Modelling: • 3 to 7-day forecasting • Early warning	Trigger levels are key;
	– Assessing model uncertainty – Nutrient fluxes & loads	Metrics are based on scientific method, auditable and verifiable.
	– Near real time requirement (<= 24 h) – Long term trend requirement	– Ecotoxicity – Pesticide residues – Integrated query system (in situ, models, EO)
	EO and in-situ based calibration of Hydrodynamic & biogeochemical & algal growth model.	

5.2.2 Thermal Imaging

Thermal imaging allows for measurement of the temperature of the very top layer of a water body, known as the 'skin temperature'. While the temperature of the bulk of a water body is not directly accessible by remote sensing, a knowledge of currents, the degree of mixing, weather trends and other factors can allow for estimation of the entire water body temperature. This modelling and time series of interconnected water bodies would be critical to delivering the preferred 'water body temperature' which many end-users desire.

Table 4: AquaWatch end user requirements/goals for thermal imaging

Parameter/Requirement	Breakthrough	Target
Ground resolution	30 m	10 m
Orbital revisit time, all water bodies in Australia	5 Days	< 5 Days
	Less for Reporting of trends, State-of-the-Environment	
Quantities of interest: directly observable	Surface Skin Temperature on Lakes, Reservoirs, Rivers, Deltas, Estuaries, Lagoons	Water Body Temperature on Lakes, Reservoirs, Rivers, Deltas, Estuaries, Lagoons

5.2.3 Water quantity estimation

Satellite estimation of water quantity in water bodies is also of critical importance in many industries. Accurate measurements of the extent and depth of water bodies require a combination of accurate knowledge of terrain, and the extent of water bodies as viewed from above.

Table 5: AquaWatch end user requirements/goals for water quantity

Parameter/Requirement	Breakthrough	Target
Ground resolution	30 m	10 m
Orbital revisit time, all water bodies in Australia	5 Days	< 5 Days
	Less for Reporting of trends, State-of-the-Environment	
Quantities of interest: directly observable	Water level in Lakes, Reservoirs, Rivers, Deltas, Estuaries, Lagoons	Water quantity and fluxes in Lakes, Reservoirs, Rivers, Deltas, Estuaries, Lagoons

5.2.4 Summary of End-User Requirements

5.2.4.1 Spatial resolution

End-users deemed that a system providing a ground pixel resolution between 10-30 meters could meet most of the requirements for water quality monitoring. The inland water bodies that need to be monitored vary in size from rivers to lakes and estuaries. A 10 m GSD would allow for a greater number of water bodies to be included in the monitoring mission. However, a smaller GSD has implications for the achievable instrument SNR and the number of pixels on the FPA to cover the desired swath.

5.2.4.2 Spectral resolution

A spectral resolution or spectral sampling interval of between 5-8 nm would allow the instrument to provide image products with a level of spectral fidelity to meet the water monitoring mission. A spectral bandwidth of between 7.5 - 12 nm would provide the needed channel throughput to provide adequate signal to noise ratio (SNR). There is a fundamental relationship between spectral sampling and spectral bandwidth to optimise the spectral sensitivity of the instrument and to adequately synthesize the bandpass of multi-spectral instruments and this is reflected in the required values.

5.2.4.3 Radiometric resolution

The radiometric resolution or sensitivity in the VNIR/SWIR bands is defined by the noise equivalent change in radiance. This is the change in input radiance to the instrument that produces a change in the sensor response which is equal to the total noise of the sensor. Any change less than this value cannot be registered above the noise floor of the system. The values in the initial specification reflect the sensitivity needed to achieve the AquaWatch mission goals.

5.2.4.4 Temporal resolution

Temporal resolution is important, and shorter revisit times (more frequent opportunities to image areas of interest) allows AquaWatch to provide greater benefits to users.

Most EO satellites are in specific polar orbits whose altitude and inclination are calculated so that a single satellite sensor will observe, over time, the same scene with the same angle of solar illumination. The revisit time for a satellite will be longer at the equator than in polar regions and so can be specified at a given latitude.

From the point of view of the satellite, the revisit time is the elapsed time before the satellite retraces its ground track, passing over the same point on the ground. (This should be termed the revisit cycle of the spacecraft rather than revisit time).

The revisit time can also be defined as the length of time to wait for a satellite sensor to be able to observe the same point on Earth but not necessarily at a nadir view and under the same illumination conditions.

The difference between these two definitions originates from the ability of a spacecraft to perform station keeping and slew manoeuvres in both the cross-track and in-track directions as well as accounting for the field of view of the sensor. This results in a lower revisit time when defined as the elapsed time between opportunities of a spacecraft sensor to see the same region of interest on the ground.

The primary observable region of interest is also important in determining the mission architecture. For example, the Italian 'PRISMA' mission is a single spacecraft with a published body pointing capability of ± 15 degrees and a primary region of access bounded by ± 70 degrees latitude since Europe and the Mediterranean are of most interest[3]. The European 'Sentinel-2' has a different orbit, primary region of interest ,and with two spacecraft provides its mission level revisit time for both a single spacecraft and for two spacecraft within its primary regions of interest[4]. As noted with the Sentinel-2 example, the time between observations of the same scene can be decreased using a constellation of satellites carrying the same senor since there are more opportunities to observe a region of interest.

In this study, the revisit time is not the revisit cycle of the spacecraft and it is not restricted to nadir views. It is assumed that a target within the region of interest can be acquired within the field of view of the sensor and at view angles between the target and the spacecraft of between zero and at least twelve degrees (which may be preferable since off nadir views could provide a reduction of sun glint over water bodies). Since the AquaWatch primary region of interest is Australia the revisit time should be defined within ± 45 degrees latitude. For a satellite at 560 km in a near-polar sun synchronous orbit within a ±30 degree field of view then the revisit time at the Equator is ~4 days and ~3 days at ±45 degrees latitude[5].

Through the CEOS feasibility study, the CSIRO end-user consultation process, and in this CDF study, a trade-off between spatial resolution and revisit time has emerged. The monitoring of water bodies of interest in Australia, and the aquatic species which reside in them, require a spatial sampling on the order of meters rather than tens or hundreds of meters. A high ground resolution instrument generally provides narrow field of view. Because of this, the swath width is narrow and revisits at a given location on the ground will be more infrequent for satellites with a narrower field of view. A more detailed analysis is required to determine the revisit rate for single spacecraft and a constellation that considers the achievable swath and the target acquisition and solar illumination constraints that can be tolerated. However, a constellation of satellites is likely needed to meet the frequent revisit rates requested by end users.

5.3 Trade-Offs and Baseline requirements selection

Development of satellite requirements involves the technical translation of these end user requirements into satellite, payload and orbital parameters for the design. Drawing on the work from the CEOS report and the scientific and engineering expertise of the CDF team, a single set of payload requirements were generated, shown in Table 6.

End-users deemed that a system providing a ground resolution between 10-30 m and a spectral resolution between 5-8 nm could meet most of the end user requirements for water body monitoring. In addition, a revisit time between 2-5 days for water bodies in Australia was seen as useful.

Through the CEOS feasibility study, the CSIRO end-user consultation process and in this CDF study, a trade-off between spatial resolution and revisit time has emerged. The monitoring of water bodies of interest in Australia (especially inland waterways) and the aquatic species which reside in them require a spatial sampling on the order of meters rather than tens or hundreds of meters. A more refined ground resolution implies a narrower field of view payload imaging system which creates a smaller sensor footprint on the ground. This also means that the satellite(s) must have more overpasses to cover the same area on the ground and thus longer revisit times. Of course, a constellation of two or more spacecraft would provide a solution that reduces the revisit time.

In this study three mission concepts, each with slightly different performance requirements were explored. Preliminary analyses performed during the CDF study elicited a more detailed set of payload and spacecraft parameters. This approach focused the efforts during the initial CDF sessions on finding a feasible technical solution that would serve as an anchor point for alternative mission options.

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[3] http://prisma-i.it/index.php/en/news/program2/92-news-2
[4] https://sentinel.esa.int/web/sentinel/user-guides/sentinel-2-msi/revisit-coverage
[5] Jacobsen, K., "Characteristics of very high-resolution optical satellites for topographic mapping", International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XXXVIII-4/W19, 2011, ISPRS Hannover 2011 Workshop, 14-17 June 2011, Hannover, Germany

This first concept is labelled as "strawman" mission in Figure 3. For this concept, a payload was conceptualised to subsequently define the satellite that would host this payload. Cost, schedule and risk assessment were performed for the strawman mission concept. The strawman mission concept is labelled as "Option A" in this report.

The later CDF sessions were dedicated to identifying areas where Option A could be altered to provide further insight into the mission concept trade space. During the study, it was decided that identifying mission concepts with a reduced cost target would be most useful. These options were then qualitatively assessed by identifying changes with respect to Option A. These concepts are labelled as "Option B" and "Option C" in this report.

The parameters in Table 6 represent demands that at least meet or exceed the end user requirements listed in Table 3, being the requirements for a hyperspectral imaging instrument. While a thermal infrared imaging instrument and accurate estimates of water quantity were strongly requested by the end users in our consultation, we chose to focus on the hyperspectral imaging component at this stage of the study for a number of reasons that should be noted here:

- Water quantity can be accurately estimated using high spatial resolution imagery with only a few relatively broad spectral bands. These are currently supplied by existing operational satellites and do not demand a new satellite capability.
- Thermal imagery that would satisfy the requirements is also available from existing satellites. While the resolution and revisit times highlighted in the workshops is not generally met, especially for the 'preferred' requirements, thermal imagery is so widely used in many domains that a specific thermal imaging instrument for aquatic ecosystems is not justifiable.
- Hyperspectral imaging is much more domain specific, and as discussed in Section 7, it is here that the most critical gap in remote sensing coverage appears. It is the lack of hyperspectral imaging – with the specific wavelength bands, the SNR levels, and capability to image very dark water bodies – that has prompted the AquaWatch Australia satellite component development.

While the requirements listed here may not be met by the payload instruments, they are presented as a guide to creation of the specific payload specifications.

Table 6: AquaWatch Satellite Requirements – Baseline for CDF study

Requirement	Value		Unit	Note
	Breakthrough specification	Target specification		
Orbit	Sun-synchronous, 400 to 800		km	A notional 560 km chosen in analysis to meet revisit time
Pointing knowledge (APK)	0.4	0.2	pixel	Line of sight uncertainty < 500 m on ground was stated in the study. Note: A jitter requirement over given time intervals was noted in the study as important to define. Note: A geolocation accuracy would also be recommended. It would be the location error after ortho-rectification representing the deviation between the estimated coordinates and the real position of the target.

Revisit time (single spacecraft @ Equator)	5	< 5	days	Need to specify as shortest time separation between two acquisitions to the target within the constraints of allowable spacecraft look angle to the target and the time of day/sun Az and El boundaries
Sunglint avoidance	≥12	≥12	deg	A capability to tilt the spacecraft/sensor fore and aft (along track) by TBD degrees and up to 12 degrees away from sun across track.
GSD	30	10	m	
Spectral range	VIS-NIR 400-900	VIS-NIR 360-1000 SWIR 1100-1400	nm	
Spectral resolution (FWHM)	12	7.5	nm	
Spectral sampling interval	8	5	nm	
Spectral distortion (“smile”)	TBD	TBD	pixels	Typically, less than 0.2 pixel achieved in operational HSIS
Spectral co-registration (“keystone”)	TBD	TBD	pixels	Typically, less than 0.2 pixel achieved in operational HSIS
Band to band registration	0.2	0.2	pixels	
MTF (@Nyquist)	10	10	-	Specification in relative edge response is used in the remote sensing community from which MTF can be derived. [6].
SNR	200:1	400:1		End users desired SNR in the 200-400:1 range. As high as possible was noted. Note: SNR similar to EnMap or Prisma would require similarly sized telescope apertures, throughput efficiency, and low-noise, high-performance FPA and ROIC. Note: Refine WRT individual bands rather than across all bands. Note: SNRs in the 100-200:1 range are more likely to be achieved within the notional SWaP constraints for a smallsat mission.
Dynamic range	12-14	16	bits	Review 16-bit requirement WRT NEDL

[6] NASA-SLI-001 Land Imaging Requirements Rev B

Minimum radiances to be observed, L_{min}	412 nm: 30 490 nm: 16 560 nm: 10 665 nm: 5 778 nm: 2 865 nm: 1		W- m^{-2} mm^{-1} sr^{-1}	TBR
Typical radiances to be observed, L_{typ}	412 nm: 80 490 nm: 55 560 nm: 40 665 nm: 20 778 nm: 10 865 nm: 5		W -m^{-2} mm^{-1} sr^{-1}	TBR
Maximum radiances of targets of interest (inland waters and coast waters), L_{high}	412 nm: 350 490 nm: 350 560 nm: 350 665 nm: 300 778 nm: 300 865 nm: 250		W-m^{-2} mm^{-1} sr^{-1}	TBR
Saturation radiances, L_{max}	412 nm: 750 490 nm: 750 560 nm: 650 665 nm: 600 778 nm: 450 865 nm: 400		W-m^{-2} mm^{-1} sr^{-1}	TBR
Radiometric resolution (NEDL)	0.005 (based on L_{high}) 0.011 (based on L_{max})		W-m^{-2} mm^{-1} sr^{-1}	
Spectral calibration accuracy	TBD	TBD	nm	Typically, 0.1 nm achievable
Radiometric calibration accuracy (on ground)	TBD	TBD	%	On ground typically 2-3 % is state of art capability
Radiometric stability (on orbit)	TBD	TBD	%	Need to specify time period
Polarisation sensitivity (on orbit)	< 1%		%	TBC; an on-ground requirement will be derived from the on-orbit requirement
Timeliness of data	24		h	Within 24 hours for normal management use Months for long term trend analysis.
Image strip length	≥4000 km (to fit in Australia N to S in one strip)		km	Will have implications for on board memory and ground segment architecture and down-link windows
Minimum image area	TBD		km2	Based on swath and image strip length. Also see above comment
Timeliness of data	TBD	TBD		Near Real Time for extreme events-low accuracy
Compression ratio	TBD	TBD		Lossless; 2:1 capability achievable
Stray light and stray light rejection	0.2 % of typical radiance 3 pixels away from cloud			Define characteristics of this parameter
Optical and electronic crosstalk	TBD	TBD		Electronic and optical crosstalk characterisation is required. (band to band and out of band)

Striping and detector to detector response variations	TBD	TBD		Minimise during calibration

The resolution requirements for spatial, spectral and radiometric performance would be refined in a future Phase A study. The values presented here have been informed by and would follow accepted user-community definitions for these key system performance metrics[7]. The radiance levels were provided by Curtin University during the study.

[7] https://esto.nasa.gov/files/SLIT2015/RMAKeyParameters.pdf

6 Mission Options Overview

This chapter provides a description of three mission options that were developed in the CDF study. The imaging payload provides a hyperspectral imaging capability that meets the AquaWatch breakthrough requirements for spatial, spectral, and radiometric resolution.

Mission Concept A allows all breakthrough requirements (Except for AUS-wide revisit frequency) to be met while options B and C provide reduced capability but with substantial cost savings. Option B provides cost savings of approximately 50% compared to Option A but with coarser spatial and spectral resolution and a reduction in SNR. Option C provides cost savings of approximately 30% compared to Option A where the spatial and spectral resolution requirements are met but the field of view and the SNR are reduced. These options are summarised in Table 7. A Pathfinder approach is also considered as a risk reduction option to provide an iterative development path to a fully operational system. This approach is described in section 8.

Table 7: Mission Options Table

Parameter	Option A (Baseline)	Option B	Option C
Instrument type	Imaging spectrometer VNIR	Imaging spectrometer VNIR	Imaging spectrometer VNIR
Performance level	Meets threshold observation requirements, except for AUS-wide revisit frequency.	Exclude on-board calibration units (save up to AUD 10M) Reduced SNR	Exclude on-board calibration units (save up to AUD 10M) Reduced SNR
Instrument Concepts	Built by AUS-led consortium. Can be de-risked through airborne or CubeSat pathfinders. Baseline requirements & design as covered throughout this document.	Built by AUS-led consortium. Can be de-risked through airborne or CubeSat pathfinders. Use on-axis telescope, narrowing FoV. Reduced image quality (GSD vs. spectral resolution vs. SNR). Removal of optical bench and instrument calibration sub-system. Accompanied by simplified power, battery, ADC and heat mgmt. subsystems.	Built by AUS-led consortium. Can be de-risked through airborne or CubeSat pathfinders. Use on-axis telescope, narrowing FoV. Removal of optical bench and instrument calibration sub-system. Accompanied by simplified power, battery, ADC and heat mgmt. subsystems
Instrument mass	~65kg	TBD	TBD
ROM Satellite cost	~ AUD 70M	~ AUD 35M	~AUD 50M
Data downlink	X-band to AUS 9m antenna during night passes Data rate 50Mbps	X-band to AUS 9m antenna during night passes Data rate 50Mbps	X-band to AUS 9m antenna during night passes Data rate 50Mbps
Satellite mass	~180kg	≤100kg	≤100kg
ROM mission cost estimate (incl. Satellite Cost)	~ AUD 132M	~ AUD 50M	~ AUD 65M
Recurring cost estimate (subsequent satellites)	~ AUD 47M	Not investigated	Not investigated
Timeline to launch	~5 years	Not investigated	Not investigated

6.1 Mission Option A

Option A is the full operational capability mission which includes a Hyperspectral Imaging Spectrometer system (HSIS) for high-resolution spectral information and would provide performance levels comparable with the most advanced space-based units that are currently on-orbit or planned for deployment in the next few years. The instrument would be complex and likely include an internal calibration subsystem and off-axis optics to meet the needed field of regard requirements. It can be thought of as an instrument that has similar performance to those on the EnMap (Germany) and PRISMA (Italy) missions in terms of capability and design.

Options B and C provide simpler and less expensive instruments, which leads to overall savings on the satellite design and construction (with size, mass, and power all being reduced).

6.2 Mission Option B

Mission option B was developed with the goal to meet a cost target of AUD 50M. This represents a reduction of mission cost by about 62% and can be translated into a reduction of satellite cost of ~50%.

As a large fraction of the satellite cost is due to the payload, such a cost saving can only be achieved by considering reduced payload performance. The following measures allow the cost target to be met, but the exact level of performance reduction will need to be assessed in a future study.

- A direct and recurrent cost saving of about AUD 10M can be achieved by removing the on-board payload calibration subsystem. This implies that only external calibration sources can be used, for example, imaging pseudo-invariant calibration areas on Earth. This bears the risk that not all observation use cases can be met.
- The instrument optics can be simplified by pursuing a diffraction limited on-axis design. This design choice removes the need for an expensive optical bench to maintain alignment of an off-axis system. The consequence will be a reduced field of view (i.e. swath width) compared with an on-axis design. A reduction in the aperture will lead to a reduction in SNR and possibly a reduced spatial resolution and spectral sensitivity. It has been concluded, based on engineering judgement, that with current technology it will be impossible to meet the cost target without sacrifices in these parameters. To confirm this estimate, a detailed analysis will be required.

6.3 Mission Option C

The objective for mission option C is to reduce the overall mission cost, without sacrificing the key requirements of spectral and spatial resolution. The result is a ROM mission cost of AUD 65M, which includes a satellite cost of about AUD 50M.

The measures to achieve this cost reduction are like those described for mission option B above, with the following key elements:

- A direct and recurrent cost saving of about AUD 10M can be achieved by removing the on-board payload calibration subsystem. This implies that only external calibration sources can be used, for example, imaging pseudo-invariant calibration areas on Earth. This bears the risk that not all observation use cases can be met.

The instrument optics can be simplified by pursuing an on-axis design. This allows to remove the need for a complex and expensive optical bench. Although a bench will provide a stable base to control temperature and vibration-induced misalignment of the spectrometer system. In contrast to option B, option C would ensure the spatial and spectral resolution requirements are met. In order to keep the SNR at an acceptable level, this will mean a reduction of the instrument's field of view corresponding to a narrower swath width. The effect on the mission is that coverage is reduced or, in order to keep the same revisit time for the entire target area, more satellites would be required.

In the long term, option C allows modular scalability, where the coverage can be scaled up by increasing the number of satellites, but the first satellite will meet the most critical observation requirements of spatial and spectral resolution.

The resulting satellites described for Options B and C have lower performance - meaning that threshold requirements for spectral sensitivity, revisit time and swath as well as SNR may not be met. The analysis of these options highlights the price vs. performance sensitivity and the value of investment in the design and precursors to balance these.

For all options described above, we would seek to perform imager calibration using pseudo invariant targets on the Earth. For options B and C above (which exclude on-board calibration systems) this would be the primary calibration method. Aside from pseudo invariant targets on the Earth, it is possible to use other calibration targets for calibration, including using the moon as a stable radiance source and linking the calibration to a "gold standard" such as Landsat, CLARREO Pathfinder[8] or a future space-based radiometer such as the Satellite Cross-calibration Radiometer (SCR)[9] or the TRUTHS [10],[11] radiometer. This will be taken into account when refining the system design.

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[8] 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

[9] 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.

10 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.

11 NPL, Improving Earth Observation Data to Drive Improved Climate Change Modelling, https://www.npl.co.uk/earth-observation/truths, accessed 27 Jan 2021

7 Analysis of Mission Concept

The AquaWatch imaging payload is envisioned to be a HSIS that provides the performance capability needed to meet the mission requirements which were discussed in the study. The mission and instrument requirements were first summarised in the CEOS Feasibility Study for an Aquatic Ecosystem Earth Observation System, Ver. 2.0 (2018) and refined through a series of end-user workshops conducted by CSIRO in late 2020 and early 2021. In particular, the spatial, spectral and radiometric resolution capability of the payload, as well as revisit time of regions of interest, were identified as key performance parameters for the system. These parameters serve as driving requirements for the conceptual design of the payload and dictate the size, weight, and power requirements for the entire spacecraft.

In this study, three mission concepts, each with slightly different performance requirements were explored. Preliminary analyses performed during the CDF study elicited a more detailed set of payload and spacecraft parameters. These parameters were explored to define an expanded set of threshold requirements for the AquaWatch Australia space segment but in some cases were not analysed in detail. A summary is given in Table 8.

Table 8: Mission Overview

Parameter	Value	Note
Pixels across Track	2000	Accepted limit of monolithic COTS detectors on the market at present. Custom FPA could be considered to increase # cross track pixels to maintain a desired swath.
Orbital Altitude	560 km	Avoid orbits to be populated with large constellations such as Starlink and Kuiper
Telescope aperture	200 mm	Likely minimum to achieve SNR
Ground Motion Compensation	-	Not performed. Smallsat ADCS unlikely to allow
Imaging coverage	TBD	Aquatic (coastal and inland) ecosystems only
Data Downlink	TBD	High data rate X-band needed to manage data volume
GEO comms relay	-	Not considered
Across-track Slewing	TBD	Default fixed angle off-nadir Option to slew before pass
Steering Mechanism	TBD	Body pointing (no steering mirror)
Ground station network	TBD	Select individual ground stations
On-board Data Storage	TBD	1 days' worth of data

7.1 Concept of Operations

A single satellite or node in the AquaWatch constellation would be operated in the following phases:

1. Commissioning. Initiation of communications link, verification of correct operation of all subsystems, establishment of high bandwidth communications and test of imaging and onboard processing system.

2. Calibration/Validation. The satellite imager is calibrated using an onboard calibration, such as use of absorption or radiance of artificial light sources, solar diffusers, or imaging of the Moon and terrestrial targets using the vicarious calibration method to verify calibration of the instrument. The capability of

the imager and onboard processing to estimate water quality parameters, to reliably detect water bodies and clouds is validated by comparison with in-situ or other referenced remote sensors.

3. Water Quality Monitoring (normal operations). The satellite continuously images most of the daytime side of the Earth from Sun-synchronous (polar) orbit, potentially excluding very high latitude polar regions. Onboard data processing (described below) reduces the data and reformats it such that it can be used to deliver water quality estimation.

With regards to control and monitoring, the satellite would be controlled by two methods:

1. Routine operations - Mapping and automated water body imaging.
2. Tasked operations – Scheduled observations of targets of opportunity.

The satellite would be controlled from a mission operations centre (MOC) which would be responsible for:

- Overall control and monitoring.
- Logging the spacecraft's physical condition and orbit.
- Tasking or scheduling observations.
- Troubleshooting, maintenance, software upgrades and exception handling.
- Delivering suitable metadata to the AquaWatch Data Analytics system.

Control and monitoring would be achieved by UHF radio uplink, with a ground station(s) to allow at least one uplink opportunity per day. Spacecraft software would be reconfigurable, and the spacecraft will be designed so that it is resilient to Single Event Upsets and can recover from logical exceptions or failure conditions.

Note, with regards to tasked operations and scheduled satellite pointing, that operation was assumed with constant across-track attitude. (i.e. the satellite would be steerable and can point off-nadir, but its attitude is fixed (not slewing) during an overpass). Ground motion compensation is not assumed.

With regards to the downlink of Earth Observations data from AquaWatch satellites, this requires a much higher data rate. Communications would be achieved by X-band radio, with a ground station network supporting at least one (preferably several) downlink opportunities per orbit.

The data received by Ground Stations would be directed to the AquaWatch Data Analytics system; a cloud-based system comprising a Science Processing Pipeline and Data Archive. The Science Processing Pipeline will present data to seven different levels:

1. Raw satellite data

2. Calibrated satellite data

3. Satellite-referenced, spectral radiance dataset

4. Georeferenced, hyperspectral dataset

5. Georeferenced, spectral reflectance dataset

6. Georeferenced, spectral reflectance of areas of interest only

7. Water quality parameter estimates of water bodies of interest only

The Data Archive will maintain the data over time and support the development of models (including Artificial Intelligence and Machine Learning) for water quality tracking and forecasting.

7.2 Space Segment

7.2.1 Imaging Payload Concept

A strawman HSIS payload was developed from the mission and space segment requirements developed in the study as a starting point for instrument and mission concept of operations development. The requirements for AquaWatch were compared to the performance capabilities of other hyperspectral imaging spectrometers that have been launched or are in the planning stages.

Table 9 summarises the AquaWatch instrument performance compared to other on-orbit science mission hyperspectral imaging spectrometers such as PRISMA and EnMap, and those in the planning stages such as SHALOM and HyPixm. To meet mission requirements an AquaWatch payload must deliver spatial, spectral and radiometric performance that is comparable to that of the best HSIS currently operating. This will pose significant technical and program execution challenges to the Australian space industry in the near term.

Table 9: AquaWatch Payload Compared to Closest Analogues

System Parameters	AquaWatch	EnMap	PRISMA	SHALOM	HyPixm
Orbit – SSO (km)	560	653	615	640	660
Imaging mode	Pushbroom	Pushbroom	Pushbroom	Pushbroom	Pushbroom
GSD (m)	30(BT) / 10 (T)	30	30	10 (PAN 2.5)	15
Swath (km)	20 (BT)-60 (T)	30	30	10	16
VNIR spectral range (nm)	400-1000 (BT)	420 - 1000	400-1010	400-1010	400-1100
SWIR spectral range (nm)	1100-2400 (T)	900 - 2450	920-2500	920-2500	1100-2500
Spectral channel width- FWHM (nm)	12 (BT) /7.5 (T)	8	10	10	10
Spectral sampling interval (nm)	8 (BT) / 5 (T)	6.5	10	8	10
VNIR SNR (at ref radiance) *	≥100:1 (band dependent)	200:1 500:1 (@495 nm)	200:1 600:1 (@ 650 nm)	200:1 600:1 (@ 650 nm)	250:1
Radiometric accuracy (%) (on-orbit)		5	5	4	TBC

	5 (BT) / 3 (T)				
NEDL (W- m^{-2} mm^{-1} sr^{-1})	0.005 (TBR)	0.05	0.1	TBC	TBC
Dynamic Range (bit)	14 (BT) / 16 (T) (TBR)	14	12	12	TBC
Compression (lossless)/compression ratio	YES	JPEG2000 / 1.6:1	1.6:1	1.6:1	1.6:1
Revisit time @ equator (day) **	3- 5	4	4	4	4

- SNR is dependent on the at-aperture radiance to the sensor (see below). AquaWatch SNR is calculated using the Lref provided in the study. The published SNR for other HSIS is provided for comparison but the Lref used to compute the SNR for those systems was unknown during this study.*
- Revisit time (approximate) calculated at the Equator considering a field of regard of ± 30 degrees**

This concept design was guided by the preliminary mission and operational requirements. An SSO orbit of 560 km altitude was selected which determines the ground track velocity and integration time for the sensor. The GSD and swath width (G) determine the necessary Field of View (FoV) of the imaging system as well as the number of cross track pixels on the detector. A comparison of these values with other hyperspectral systems is shown in Table 10.

The key issue with hyperspectral sensors, which by definition are required to split incoming light into numerous spectral bands, is the goal of achieving a sufficient signal to noise ratio at the required spatial resolution. Only a handful of commercial options exist for the key components such as the detector array. It will be noted in Table 9, that the AquaWatch design seeks to both improve on the spatial resolution achieved by the Germany and Italian mission designs, whilst simultaneously looking to increase or perhaps double the SNR. This is a significant challenge that has significant implications for the nature of the optical systems employed and their size in particular. In reality an AquaWatch sensor that is integrated on a smallsat in the 100-200 kg class will not be capable of high SNR across broad ranges of the spectrum. An achievable broad band SNR is expected to be in the range of 100-200:1.

Table 10: AquaWatch Orbital Considerations Compared to Closest Analogues

Operational Parameter	AW	EnMap	PRISMA	SHALOM	HyPixm
Altitude (km)	560	653	615	640	660
➔ Vg (m/s)	6820	6832	6886	6849	6820
GSD (m)	20	30	30	10	15
➔ Tint (msec)	2.932	2.927	2.904	2.920	2.200
G (km)	40	30	30	10	15
➔ FFOV (deg)	3.47	2.63	2.79	0.90	1.31
➔ N xtrack (pixels)	2000	1000	1000	1000	1000

A 200 mm entrance aperture three-mirror optical system was chosen to provide the required geometric image quality. These types of reflective telescopes provide diffraction-limited performance over reasonable fields of view and across the visible, near-IR and SWIR spectral bands. A COTS focal plane assembly deploying 30 um square pixels provides the needed SNR and radiometric resolution (where the optical system focal length is a derived value to meet the GSD requirement). Table 11 lists the aperture size, focal length and pixel size for the baseline payload and other spectrometers.

Table 11: AquaWatch Optical Path Specifications Compared to Closest Analogues

Design Parameter	AW	EnMap	PRISMA	SHALOM	HyPixm
Aperture diameter (mm)	200	174	210	600	430
➔ OTA type	TMA off axis	TMA off axis	TMA off axis	4 mirror Korsch	TMA off axis
Focal length (mm)	1000	522	620	1800	1720
➔ FN	F/5	F/3	F/3	F/3	F/4
p (μm)	30	24	30	30	40
➔ Q = λFN/p(@600 nm)	1.0	0.75	0.6	1.4	0.6
➔ IFOV = GSD/H=p/f (μrad)	30.3	46.1	48.4	16.6	22.7

The spectrometer is envisioned to be a single slit option with a 1:1 Offner all reflective relay where the dispersive element is a grating embossed on the Offner secondary mirror. Typical spectrometers of this type are designed to provide extremely low spectral and spatial dispersion on the order of 0.1-0.2 of the pixel dimension.

The focal plane could be a silicon CMOS sensor for visible imaging or a cooled back-thinned MCT detector for VNIR and SWIR imaging. There are several European and American vendors that could provide a space qualified sensor and front–end electronics for the focal plane assembly. It was noted that ITAR issues would need to be factored into the procurement process not only for sensors but other components. Table 12 presents a summary of these parameters and a comparison with other spectrometers.

Table 12: AquaWatch Camera Architecture Compared to Closest Analogues

Spectrometer Design Parameter	AW	EnMap	PRISMA	SHALOM	HyPixm
Spectrometer type	Grating; Single slit; single spectrometer/FPA	Grating; Dual slit -split field; separate VNIR and SWIR spectrometers	Prism; Single slit; dichroic splitter; separate VNIR and SWIR spectrometers	Prism; Single slit; dichroic splitter; separate VNIR and SWIR spectrometers	Single slit; single spectrometer/ FPA
Optical layout	1:1 Offner	1:1 Offner	1:1 Offner	1:1 Offner	1:1 Offner
Keystone (pixel)	0.2	0.2	0.1	0.1	?
Smile (pixel)	0.2	0.2	0.1	0.1	?
FPA VNIR / SWIR	e.g. Sofradir (VNIR/SWIR); E2V IC-35-02208; 2000 x 320 CMOS (VNIR)	Si CMOS (Fairchild); MCT cooled (AIM)	MCT-CdZnTe removed; MCT cooled (Sofradir)	MCT-CdZnTe removed; MCT cooled (Sofradir)	
FWC		~ 1M			
Read noise (e-)					

The concept was developed with an emphasis on using TRL 9 subsystems and components. Trade-offs could be explored to provide cost and schedule savings or to develop a bespoke FPA..

The radiometric performance of the payload was calculated based on the optical system and detector properties and using a set of at-aperture spectral band radiance values provided by Curtin University. The relationship between the payload generated signal (in number of photoelectrons) and the system parameters and input radiance is governed by the following equation;

$$S(e-) = [(\pi * p^2 * t_{int} * n_{TDI}) / (4(f/D)^2 * hc)] * \int_{\Delta\lambda} \eta(\lambda) * L_{ref}(\lambda) * \tau(\lambda) * \lambda \, d\lambda$$

Where the signal S has the following functional dependencies on the system parameters.

Table 13: Camera Design Parameter Definitions

Design parameter	Description	Signal dependency
Lref	At aperture radiance	**Lref**
p	Pixel width	**p^2**
f	Focal length	**$1/f^2$**
D	Telescope aperture diameter	**D^2**
Q	λ f / p	**Q^2**
t_{int}	Integration time	**t_{int}**
$\eta(\lambda)$	Spectral quantum efficiency	$\eta(\lambda)$

An initial estimate of the SNR was calculated assuming an 8 nm rectangular spectral band around each of the defined centre wavelengths (the spectral sampling interval is assumed to be 5 nm) where the overall throughput for the payload was 50% and the quantum efficiency of the detector was assumed to be a typical COTS CMOS device.

The preliminary SNR results are displayed in Table 14. A baseline F/5 system shows modest performance but well below that associated with other high-performance systems using the reference radiance levels supplied by Curtin University. Refinement of target radiance values, spectral throughput and quantum efficiency would likely boost these values. However, a 400:1 broadband SNR is not feasible with such a spectrometer.

Table 14: Preliminary SNR Results

Wavelength (nm)	Reference radiance(W/m2-um-sr)	SNR (F/5, 1000 mm focal length instrument providing a GSD = 20; spectral channel width = 12 nm; at ref radiance levels)
412	80	**78**
490	55	**92**
560	40	**98**
665	20	**76**
778	10	**50**
865	5	**24**

7.2.2 Satellite Bus Sizing

The satellite bus has been roughly sized based on estimated payload requirements in terms of size, weight, and power. A ROM sizing of satellite mass budget, based on expected subsystem sizes, is given in

Table 15. A preliminary mass budget produces a total satellite dry mass of ~ 170kg (inclusive of 20% margin).

Table 15: Satellite Weight Analysis

Platform				Target wet mass [Kg] :	0		Without margin [Kg]	Margin [%]	Margin [Kg]	Including margin [Kg]	% of total
Subsystem	Unit				Forced values						
	Name	Quantity	Mass [Kg]	Margin [%]	Mass [Kg]	Margin [%]					
Structure Subsystem							37.50	20%	7.50	45.00	32%
	► Primary structure	1	32.5	0.2			32.5	20%	6.5	39.0	
	Secondary structure	1	5.0	0.2			5.0	20%	1.0	6.0	
Thermal Control Subsystem							5.0	20%	1.0	6.0	4%
	Radiators, MLI, etc.	1	5.0	0.2			5.0	20%	1.0	6.0	
Attitude and Orbit Control Subsystem							9.2	20%	1.8	11.0	8%
	ADCS Computer	1	0.5	0.2			0.5	20%	0.1	0.6	
	Magnetometer	1	0.0	0.2			0.0	20%	0.0	0.0	
	Fine Sun Sensors	1	0.2	0.2			0.2	20%	0.0	0.2	
	Reaction Wheel Assembly	1	4.0	0.2			4.0	20%	0.8	4.8	
	Magnetic Torquers	3	0.5	0.2			1.5	20%	0.3	1.8	
	Star Tracker	1	3.0	0.2			3.0	20%	0.6	3.6	
Communications Subsystem							4.3	20%	0.9	5.2	4%
	X-band Tx	1	2.0	0.2			2.0	20%	0.4	2.4	
	S-band Transceiver	1	1.0	0.2			1.0	20%	0.2	1.2	
	X-band antenna	1	0.5	0.2			0.5	20%	0.1	0.6	
	S-band antenna	2	0.3	0.2			0.6	20%	0.1	0.7	
	S-band coupler	1	0.2	0.2			0.2	20%	0.0	0.2	
On-Board Data Handling Subsystem					2.0	0.2	2.0	20%	0.4	2.4	2%
	OBC	1	0.0	0.2			0.0	20%	0.0	0.0	
Electrical Power Subsystem					10.0	0.2	10.0	20%	2.0	12.0	8%
	Battery	1	5.0	0.2			5.0	20%	1.0	6.0	
	PCDU	1	1.0	0.2			1.0	20%	0.2	1.2	
	Solar arrays	1	0.0	0.2			0.0	20%	0.0	0.0	
Total dry mass without system margin							68.0	20%	13.6	81.6	
System margin								20%	16.3	97.9	
Total wet mass including all margins										97.9	

Payload				Target wet mass [Kg] :	0.0		Without margin [Kg]	Margin [%]	Margin [Kg]	Including margin [Kg]	% of total
Subsystem	Unit				Forced values						
	Name	Quantity	Mass [Kg]	Margin [%]	Mass [Kg]	Margin [%]					
Structure Subsystem					3.0	0.2	3.0	20%	0.6	3.6	3%
	Payload structure	1	10.0	0.3			10.0	30%	3.0	13.0	
On-Board Data Handling Subsystem					3.0	0.2	3.0	20%	0.6	3.6	3%
	Payload control unit	1	0.0	0.2			0.0	20%	0.0	0.0	
Payload					45.0	0.2	45.0	20%	9.0	54.0	38%
	Optical bench	1	0.0	0.2			0.0	20%	0.0	0.0	
	Foreoptics	1	0.0	0.2			0.0	20%	0.0	0.0	
	FPA	1	0.0	0.2			0.0	20%	0.0	0.0	
	Harness	1	0.0	0.2			0.0	20%	0.0	0.0	
	Thermal control	1	0.0	0.2			0.0	20%	0.0	0.0	
	Internal calibration unit	1	0.0	0.2			0.0	20%	0.0	0.0	
	Solar calibration unit	1	0.0	0.2			0.0	20%	0.0	0.0	
Total dry mass without system margin							51.0	20%	10.2	61.2	
System margin								20%	12.2	73.4	
Total wet mass including all margins										73.4	

System	Without margin [Kg]	Margin [%]	Margin [Kg]	Including margin [Kg]	
Total dry mass without system margins	119.0		23.8	142.8	
Total dry mass including system margins				171.3	
Total propellant mass	0.0	0%	0.0	0.0	
Total wet mass including all margins				171.3	

7.3 Ground Segment

The AquaWatch EO System Ground Segment will likely feature:

- One or more ground stations supporting X-band communications for payload data downlink;
- One or more ground stations supporting S-band or UHF for TT&C.

The availability of multiple X-band ground stations for data downlink will be a high priority, as the volume of data to be downloaded from each AquaWatch satellite is high and the downlink could become a bottle neck for system performance with only one station. At least two ground stations are recommended: one nationally, one internationally:

- For example, one station in Australia and one in the US station gives ~70 minutes of contact per day;
- Additional Australian stations do little to increase contact time due to the overlapping nature of the contact areas. However, a third station in a suitably chosen continent would provide added benefit. This is TBC as the satellite may become power limited when utilizing 70+ minutes/day of contact.

A 300Mbps effective downlink rate gives approximately 157GB/day. Data processing/stitching/calibration was considered out of scope. Possible radio option includes Syrlinks X-band transmitter, and an industry development option could be the development of a 1 Gbps X-band radio.

7.4 Launch Segment

We anticipate that AquaWatch would be the primary customer for a launch to inject the AquaWatch spacecraft into a desired orbit. In this study we considered launchers that have a capacity above the required launch mass with some margin. For example, the. Falcon 9 was excluded since the margin is so large. The RocketLab's Electron launcher is excluded due to its lower weight carrying capacity.

Considering the current market offerings as shown in Figure 3, we have used the example of a Virgin LauncherOne for use in initial planning based on its:

- payload capacity for SSO is just above the required value for AquaWatch.
- specific cost close to an "average" expected cost based on current provider pricing.

Figure 3: Launch Price per Kilogram – a comparison

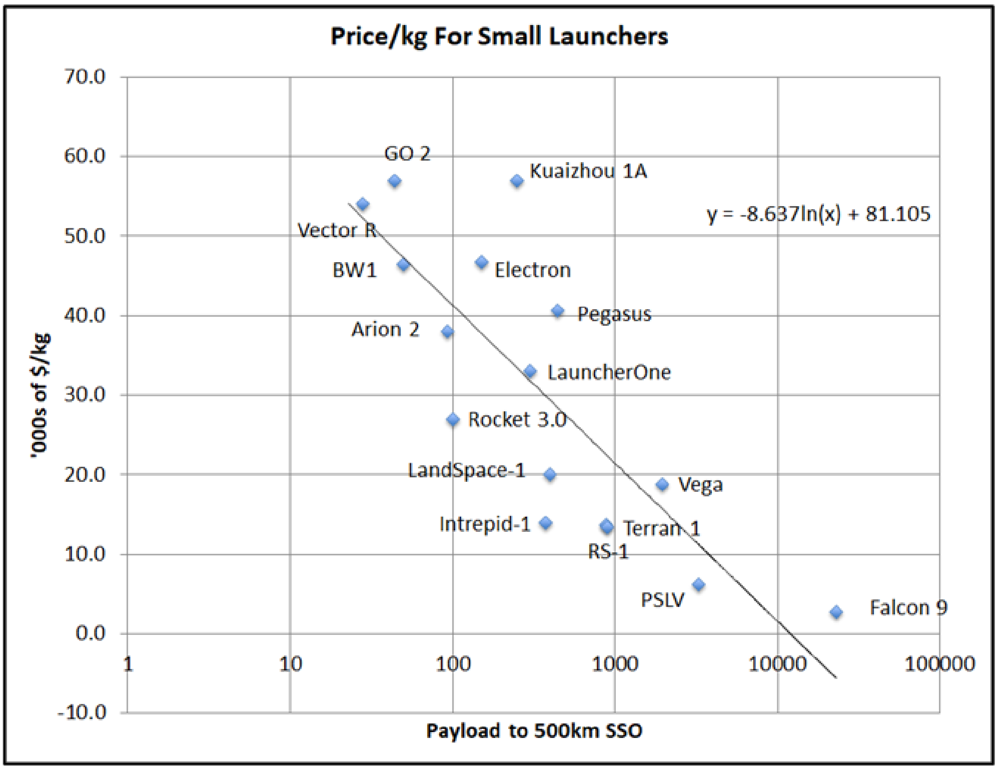

Figure supplied by Andrew Barton, Research Program Manager, Smartsat CRC. The Virgin LauncherOne would lead to launch costs of ~USD 36K/kg. It is worth noting that these figures are reasonably conservative as the market becomes more competitive and launch costs are decreasing with time.

8 Cost Analysis

This CDF study included two approaches for estimating the space segment costs:

- Each method summarises the costs of designing, constructing, and commissioning the first AquaWatch satellite. The second method also includes the cost of launch, ground segment services and operations.

- Both methods draw on historical data and experiences from similar systems built globally over the last decade. However, the estimates do not consider the positive impacts on costs of technological advances and increasing market competition.

- Large error bars have been relatively recognised due to the early nature of the mission design. But in this case the two methods produce numbers that are comparable to a first order. For design, construction, and integration of the first AquaWatch satellite, ready to launch.
  - Method 1: AUD 70M
  - Method 2: AUD 106M

The costs associated with construction of second and subsequent AquaWatch satellites will be significantly lower. This is due to the exclusion of design & NRE costs. See Section 8.3 below. Further reductions are possible with batch builds of approximately AUD 38M.

8.1 Cost Estimate Method 1

The first method used a parametric model based on system specifications and complexity to estimate the cost of satellite design and construction. See Cost and Risk Analysis of Small Satellite Constellations for Earth Observation, Nag, LeMoigne, de Weck, 2014. This method provided an estimate of ~AUD 70M.

8.2 Cost Estimate Method 2

The second method used an aggregate of costs for similarly complex (hyperspectral) EO subsystems, plus estimates for integration, commissioning and operations. The cost of launch is based on the figures in Section 7. This provided an estimate of around AUD 132M. The details behind this calculation are confidential and not shared in this document. The breakdown is shown in Table 16.

Table 16: Cost estimation method 2

Item	Cost Contribution
Project Management & System Engineering	6%
Subsystem Design, Manufacturing, Integration and Test (incl. 10% contingency)	55%
System Level Integration and Test	19%
Subtotal	80% (AUD106M)
Launch	7%
Ground Segment	1%
Operations	3%
Centrally Held Contingency (10% of total)	9%
Total	100% (AUD132M)

The comparison figure (to compare against the first method) includes the first three line-items, for a total of

AUD 106M. This compares reasonably well with the first method but is also a reasonable indicator of the error bars on this cost analysis.

8.3 Non-Recurring Engineering vs Recurring Engineering Costs

The example of a bottom-up cost estimate in Table 17 (created post-CDF) is presented to provide an insight into the split between design work/non-recurring engineering, and production work/recurring engineering. The table is consistent with the figure derived from Method 2 above of AUD 106M to design, construct, integrate and test a satellite ready for launch[12].

This view shows around AUD 38M of production and recurring engineering costs (excluding launch cost of approximately $9M per satellite) which are applicable to second and subsequent AquaWatch satellites.

Table 17: NRE vs RE Costs

EO System Project Management & System Engineering	People	Years	$M p.a.	HW Costs ($M)	Total Cost ($M)
Project Manager	1	7	0.3		2.1
System Engineer	1	7	0.3		2.1
PMA and Administration	1	7	0.2		1.4
Qualification, Regulatory Approval and Spectrum Licensing	1	7	0.25		1.8
Materials, training and travel					0.4
Sub Total					**7.8**
EO System Design Work (incl prototype) and NRE (incl verification)					
Subsystem Managers	3	5	0.3		4.5
Optical Subsystem Design & Verification	5	5	0.25	10	16.3
Payload Processor Subsystem Design & Verification	4	5	0.25	2	7.0
Data Comms Subsystem Design & Verification	2	5	0.25	2	4.5
Main Mission Module Design & Verification	3	5	0.25	1	4.8
Attitude Determination & Control Design & Verification	2	5	0.25	3	5.5
UHF Radio Subsystem Design & Verification	1.5	5	0.25	1	2.9
Electrical Power Supply Subsystem Design & Verification	2	5	0.25	1	3.5
Bus & Mech System Design & Verification	2	5	0.25	2	4.5
System Assembly, Integration & Verification	4	5	0.25		5.0
PA/QA	1	5	0.2		1.0
Training and travel					1.0
Subtotal for Design					**60.4**
EO System Production Work and Recurring Engineering					
Subsystem Managers	3	2	0.3		1.8
Optical Subsystem AIT	5	2	0.25	10	12.5
Payload Processor Subsystem AIT	4	2	0.25	2	4.0
Data Comms Subsystem AIT	2	2	0.25	2	3.0
Main Mission Module AIT	2	2	0.25	1	2.0
Attitude Determination & Control System AIT	2	2	0.25	3	4.0

[12] Figures are in Australian Dollars and assume Australian labour rates (including typical overheads). The ground segment would be owned and operated by a third party. Costs are associated with contracted ground station services, rather than construction of new ground stations. Operations covers the first 3-years, effectively covering commissioning and early operations activities. In sections 8.1 and 8.2 there is some margin/contingency on each line item used, plus an overall program contingency

UHF Radio Subsystem AIT	1.5	2	0.25	1	1.8
Electrical Power Supply Subsystem AIT	2	2	0.25	1	2.0
Bus & Mech System AIT	2	2	0.25	2	3.0
System Assembly, Integration & Verification	6	2	0.25		3.0
PA/QA	1	2	0.2		0.4
Training and travel					0.5
Subtotal for Production and Integration					**38.0**
TOTAL					**106.0**

9 Risk Analysis & Risk Mitigation

9.1 Mission Risk Assessment and Technology Maturity

9.1.1 Risk Assessment

The risk assessment that was conducted during the CDF study was not based on a set framework but was an interactive brainstorming activity to best utilise the expertise in the room. It represents a first pass at:

- Identifying the risks to the mission, including programmatic and technical risks;
- Assigning initial severity and likelihood assessments.

This early risk analysis supports future review, and it will be transposed into an AquaWatch Mission Risk Register during AquaWatch Phase A. Importantly the risk analysis, even in its most basic form, supports development and prioritisation of mitigating actions (see following subsections on TRL Analysis and Pathfinders). The following matrix categorises the identified risks in terms of type/impact and likelihood.

Table 18: Risk Table

	Negligible	Significant	Major	Critical	Catastrophic
Maximum Likelihood		Funding cut for operations	Very large number of stakeholders to manage. Biggest or most complex attempted satellite project in Australia	Project management / governance within a multi-organisational partnership.	
High Likelihood	Launch delay due to issues external to project	Unsuitable Collaboration tools Degradation of imaging quality over lifetime worse than anticipated Quality control of procured items Failure to consolidate mission/operational/ performance requirements Competing satellites with similar or better specs become available Delays in delivery of hardware or software from suppliers	Construction budget is underestimated Construction schedule is underestimated Error made in translating system specs to component specs Underestimate of compliance/qualification activities Key expertise needed for project not available when needed	Unsuitable PM and SE processes. Reaction wheel failure	

	Negligible	Significant	Major	Critical	Catastrophic
Medium Likelihood		Changes to CSIRO or SmartSat CRC priorities force replanning. Unavailability of required test facilities. Short schedule leads to technical failure. Contractual disputes over procured goods and services. Product warranty issues. Underestimate of effort/time for spectrum licensing. Mechanical failure during AIT	Uptake of AquaWatch data products. Incomplete or inadequate testing. Products/subsystems do not meet performance requirements. Overseas supplier management and procurement challenges. Limited/no value to international partners (e.g. Sentinel) Restrictions to travel or shipping. Delays in delivery of major subsystems for system integration Schedule runs overtime for the development of software. Pointing inaccuracy Payload specification leads to unavailable component choices. Final product does not (fully) meet end user needs. Cost Overruns Cleanliness requirements too demanding for existing facilities Commissioning of the spacecraft takes longer than expected	System has a very high operating cost Scope / requirements creep Loss of stakeholder/sponsor support. ADCS electronics or software failure leading to loss of spacecraft attitude knowledge/control	

	Negligible	Significant	Major	Critical	Catastrophic
Low Likelihood		Substantial launch delay due to spacecraft development problems Trade controls preventing import of required components. Ground station availability at AQW overpass time.	Subsystem design flaw (power, thermal, ADCS, etc) uncovered during AIT campaign resulting in substantive redesign Dimensional stability in space environment of optical payload assembly	Failure during vibration testing Imaging payload gets damaged or goes out of alignment during launch	Failure during LEOP
Minimum Likelihood				Damage to integrated spacecraft during ground handling or transportation Electronics damaged by radiation	Space debris collision Launch failure

9.1.2 Technology Readiness Assessment

During the CDF study we performed a "Technology Readiness Level (TRL)" assessment of the subsystems, components and services that are required to construct and commission AquaWatch

TRLs are expressed by a number from 1-9, where 9 represents the highest level of technology readiness. TRLs are a commonly used engineering principle, and definitions vary slightly from one source to another. We have used the following NASA definitions:

TRL9: Flight proven though successful mission operations

TRL8: System integrated, and flight qualified through test and demonstration

TRL7: System prototype demonstration in a space environment

TRL6: System/subsystem model or prototype demonstration in a representative environment

TRL5: Component or prototype evaluation in a relevant environment

TLR4: Component or prototype validation in a laboratory environment

TRL3: Analytical and experimental critical function and/or characteristic proof-of-concept

TRL2: Technology concept and/or application formulated

TRL1: Basic principles observed and reported

Table 19 and Table 20 summarises our assessment conducted during the study of potential AquaWatch subsystems, components, and services, and show a reasonable degree of maturity in those currently available for the construction of the system.

In the case of a system like AquaWatch, we would strive to use components & services with a high degree of maturity and proven suitability. That implies technology readiness levels of 8 or 9. There are some areas where the technology readiness is currently too low. However, this is mitigated through several avenues:

- ❖ The rapidly improving maturity of the Australian Space Industry and the expected improvement in TRLs of locally sourced products and services over the next few years.

- The ability to source products and services globally, where there is much more choice and competition, and where TRLs for the required technology is also improving.
- The ability to identify and perform targeted R&D through the AquaWatch precursor program.
- The ability to collaborate and push technology, particularly where there is potential design reuse or commonality with parallel missions in Australia.

Table 19: Component TRL Analysis

Element	Subsystem	Item	Performance	Option	Current TRL	Expected TRL8	Example equipment/ provider	Comment
Launch	Launcher	Launcher	200kg into SSO	Worldwide	TRL 9			
	Launch facility			AUS	TRL 5	2023	Southern Launch, ELA, QLD launch facility	Estimate based on public information
Ground	Data processors	Pre-0 Stitch	CCSDS conform	Worldwide	TRL 9			
				AUS	TRL 9			
		L0	CCSDS conform	Worldwide	TRL 9			
				AUS	TRL 4	2023	GA development (internal or contract)	Low risk
		L1		Worldwide	TRL 9			
				AUS	TRL 6	2023	GA development (internal or contract)	Low risk
		L2 - Top Of Atmosphere, Calibrated Data		Worldwide	TRL 9			
				AUS	TRL 9			
	Ground Stations	Ground Stations		Worldwide	TRL 9		Several choices including GA existing assets	
				AUS	TRL 9		GA existing assets	
Space	Payload	VSWIR Camera	General hyperspectral	Worldwide	TRL 9 TRL 4	2022	HyperScout, Hyperspace, Headwall, Brandywine	TRL9 at lower spec. TRL4, and improving, at similar spec.
			Full spec compatible	Worldwide	TRL 4-6		NASA JPL, Leonardo, OHB, Kari, Ball Aerospace, Teledyne, Elbit	
			Full spec compatible	AUS	TRL 4-5		ANU, CSIRO, Sydney University, BAE Systems etc.	

Element	Subsystem	Item	Performance	Option	Current TRL	Expected TRL8	Example equipment/ provider	Comment
		Internal Calibration Unit		Worldwide	TRL 5	2022 (12-18 months)		Components are COTS, but systems are custom built
		On-Board Processing Algorithms		Worldwide	TRL9			
				AUS	TRL8			
	Platform	Avionics		Worldwide	TRL 9		SSTL, Sitael etc.	
		Platform Control		AUS	TRL 7-8		UNSW, Inovor	Unlikely to be suitable given the mission profile (rad-hardened etc.), or have sufficient storage capabilities
		Payload Data Handling		AUS	TRL 5		UNSW, CSIRO, Fleet	
		PL downlink antenna		Worldwide	TRL 9			
				AUS	TRL 5			Specification TBD, groups exist in AUS to develop an antenna
		X-band Tx	50Mbps	Worldwide	TRL 9		General Dynamics, Syrlinks	Lower data rate modems are very common and low risk.

Element	Subsystem	Item	Performance	Option	Current TRL	Expected TRL8	Example equipment/ provider	Comment
				AUS	TRL 2		Inovor UNSW Cingulan Space	Low TRL specifically for this emerging high-data rate technology. No evidence of current development. Cingulan possibly?
		ADCS Components	3arcsec knowledge accuracy	Worldwide	TRL9		Blue Canyon Sinclair Orbital Bus systems: York Space, SSTL, Photon, etc.	Sizing and component integration is likely.
			ADCS	AUS	TRL 7	2021	UNSW, Inovor	Sizing changes required
			STR	AUS				None identified
		EPS		Worldwide	TRL 9			
				AUS	TRL 6		Inovor	None identified
AIT	Test facilities	TVAC		Worldwide	TRL 9			
				AUS	TRL 9		AITC2	Sizing may be marginal. NSW govt. looking at building a dedicated satellite Integration Test Facility.
		Shock and vibe		Worldwide	TRL 9			
				AUS	TRL 9		AusTest, VIPAC	Cleanliness needs improving
		EMC chamber		Worldwide	TRL 9			

Element	Subsystem	Item	Performance	Option	Current TRL	Expected TRL8	Example equipment/ provider	Comment
				AUS	TRL 9			Either not clean, or size is marginal
		Acoustic testing		Worldwide	TRL 9			
		Instrument calibration		Worldwide	TRL 9		NASA JPL, NASA Goddard, UK NPL	
				AUS	TRL 5-6		DST, CSIRO	TBD whether all requirements will be met
	Integration facilities	Cleanroom for integration		Worldwide	TRL 9			
				AUS	TRL 8		AITC, Linfield, Marsfield	

Table 20: Services TRL Analysis

Element	Discipline	Option	Current TRL	Expected TRL8	Example Organisations	Comment
Space	FSW development	Worldwide	TRL 9			
		AUS	TRL 8		UNSW, Fleet, Inovor, CSIRO, Myriota	
	System integration	Worldwide	TRL 9			
		AUS	TRL 5		(Inovor, UNSW, CSIRO)	Standard-based engineering approach will be required for AquaWatch
	System verification	Worldwide	TRL 9		Many	
		AUS	TRL 5	2023	(UNSW, Inovor, CSIRO)	More complex, standard-based engineering approach will be required for AquaWatch
	Operations	Worldwide	TRL 9			

		AUS	TRL 4-8	2024	Optus, CSIRO (UNSW, Fleet, Saber Astronautics, DST)	Except for NovaSar, lower complexity mission operations. Operations are in place for demonstrator capabilities
	Internal Calibration unit AIT	AUS	TRL 5		CSIRO, DST	
	Advanced on-board processing algorithm development	Worldwide	TRL 8			Demonstrators
		AUS	TRL 7	2023	CSIRO, DST	Not necessarily in SWaP-limited environments
	ADCS Integration	Worldwide	TRL 9		Blue Canyon, Adcole Maryland	
		AUS	TRL 7		UNSW, Inovor	

9.2 Pathfinders

An assessment was performed to understand how pathfinder missions could mitigate specific risks associated with the full operational capability mission. This approach allowed us to study three mission scenarios and various pathfinder opportunities to a level of detail sufficient to obtain a first understanding of the AquaWatch mission's technical feasibility and its ROM scope and complexity. The study also identified the key technical challenges and next steps to be taken on a path towards implementation.

9.2.1 Opportunity

The AquaWatch mission defines "Pathfinders" as stand-alone systems that are designed and built under the AquaWatch mission to demonstrate the system (design and operations) in a representative way. A Pathfinder should aim to provide a high degree of design reuse, representative data sets, and possible integration into the final system.

Importantly, Pathfinders provide significant opportunities to identify AquaWatch risks and examine mitigation strategies for technical and programmatic risks, provide an opportunity to launch and improve the TRL level of future subsystems/components, and improve the capability of Australian space industry manufacturers and developers. Pathfinders also provide a platform to undertake Targeted R&D activities to improve system capabilities and optimise performance and cost benefits.

The following objectives have been identified to be potential pathfinder objectives:

- Establish local partnerships
    - Support and leverage local capability
    - Identify and address gaps in local capability
    - Engage industry early to let them understand the needs of AquaWatch.

- Understand design trade-offs
    - Including model-based system engineering and system simulators
    - Establish system budgets and facilitate correct functional partitioning
    - Refine system architecture and subsystem specifications to optimise system functionality and performance against construction costs and risks
    - Validate mission concept towards user requirements.

- Build a community around AquaWatch
    - Support the early involvement of water scientists, with provision of representative data sets in areas and applications of interest
    - Support the early involvement of our broad base of water end users, through the ability to address real water quality issues, and demonstrable impact in key applications of AquaWatch
    - Communicate system validation and evaluation activities, which help maintain the overall AquaWatch business case
    - Maintain the support and involvement of Stakeholders and Sponsors through a compelling business case and a system that remains practical and feasible to build.

- Risk mitigation
    - Opportunities to address TRL improvements, including opportunities for flight heritage
    - Opportunities to address mitigation strategies for most technical risks
    - Risks may be specific to the satellites, or they may be related to the ground segment, the end-to-end processing chain, or vertical integration and system operation
    - Risks that can be mitigated also include programmatic ones, testing governance and management frameworks for the mission, as well as partnerships and IP ownership.

- A pathfinder mission also introduces new risks:
    - Delay of operational AquaWatch mission

- Distraction from operational mission
- Cost increase of whole programme
- Probity and possible conflict of interest due to working with pathfinder contractor.

9.2.2 Mission options

There was a discussion around Pathfinders that would address most of these objectives within the CDF study. The following rating in Figure 4 was given by study participants to applicable, existing or planned pathfinder opportunities:

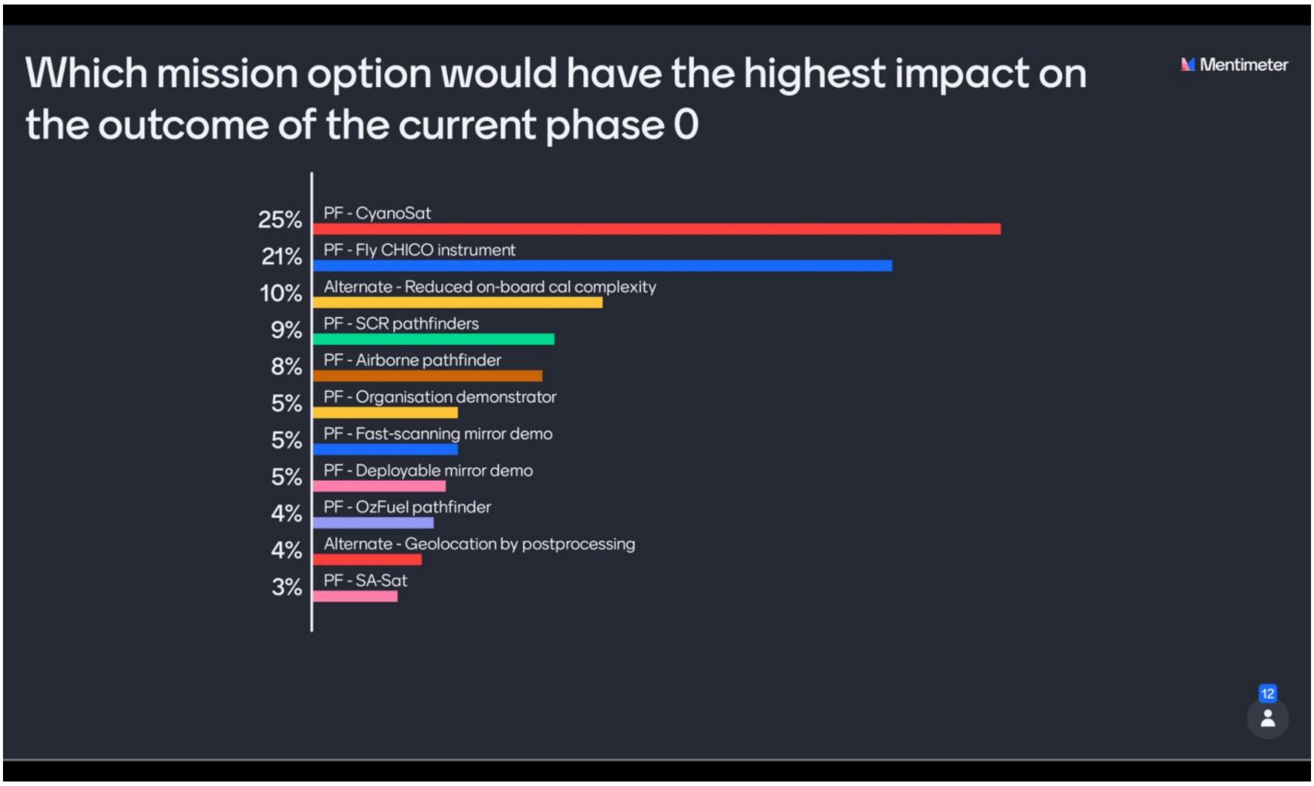

Figure 4: Highest impact on the outcome of current Phase0_survey results

The CyanoSat and CHICOSat concepts have emerged throughout Phase 0, as our general understanding of the AquaWatch mission and its needs has emerged. They are envisaged as precursor CubeSats designed and built under the AquaWatch mission to demonstrate the system, prove the technology (R&D, TRLs, risk mitigation), resolve outstanding trade-offs, support iterative approaches to Software Development and provide representative data to end-users. This CDF study not only supported the pursuit of these precursors, but it also informs their scoping.

- The “CyanoSat” pathfinder would be designed specifically for detection of cyanobacteria and harmful algal blooms. This satellite would utilise a multi-spectral camera and be a relatively simple design, with lower specifications than the planned AquaWatch satellites. This would aid in optimising the AquaWatch satellite design by confirming the model-based systems engineering approach that that is applied to the dynamic range of AquaWatch satellites. The CyanoSat would additionally demonstrate a vertically integrated and operational system, including downlink, data processing and data archiving. CyanoSat would provide valuable & representative data to end-users and have an immediate impact on management of water resources in Australia. This project would be similar in size and scope to the SASAT-1 mission[13].

[13] https://www.inovor.com.au/south-australia-to-launch-australian-first-satellite-mission/

- The “CHICOSat” pathfinder would be designed specifically to provide flight heritage to a representative Hyperspectral Imager. In this case we would aim to use the CHICO (CubeSat Hyperspectral Imager for the Coastal Ocean) instrument designed by the ANU, in partnership with DMTC, CSIRO and Skykraft. This precursor project would focus on the verification of the CHICO instrument against its own specifications (performance and functionality), but in doing so it will provide significant TRL boost to local capabilities in space-ready hyperspectral camera design & construction. CHICOSat would also compliment development of simulations and models of system performance and contribute to the assessment of On-Board Calibration systems needed for AquaWatch. Like CyanoSat it would provide valuable & representative data to end-users and have an immediate impact on management of water resources in Australia. This project would be slightly larger than CyanoSat due to the step-up in optical system complexity[14].

[14] https://dmtc.com.au/news/partners-tuning-up-for-innovation-success

10 Recommendations and Open Points

Several open points were identified during the study that should be addressed as part of future Phase A engineering activities and could be refined in subsequent phases of the project.

The study makes the following recommendations.

1. Analyse the feasibility and trade-offs around the payload signal to noise and spatial resolution, including selection of detector arrays and telescope formats.
2. Develop a detailed pointing budget for the spacecraft to establish that imaging and georeferencing requirements can be met.
3. Develop an end-to-end image chain simulator to enable quantitative trade-offs so performance and cost can be realised. This should include a final clarification of SNR needed to meet user needs.
4. Conduct an analysis of station keeping requirements to include and inform the anticipated need of on-board propulsion.
5. Analyse the feasibility of including a higher transmission rate (e.g. > 250 Mbps) X-band communications subsystem.
6. Analyse the achievable revisit time for different constellation options versus the user requirements in a cost-benefit study. Employing a larger constellation of cheaper satellites will be investigated, and a satellite design (such as that described in Option C above, which excludes on-board calibration) will be considered more closely.

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:

1. A hyperspectral instrument meeting all observation requirements as identified including the facilities to assemble and integrate it.
    a. 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.
2. A micro-satellite on-board calibration subsystem for a hyperspectral payload to achieve radiometric accuracy and stability requirements.
3. A high-data rate payload data handling subsystem for micro-satellites capable of simultaneously reading and writing hyperspectral data streams.

The business case should include the development of science algorithms to support AquaWatch end-user and stakeholder data/image product needs.

Several open points remain but can be addressed in future project phases. These include;

1. A decision on the need for pathfinder and if so, which objectives a pathfinder shall meet.
2. Activity to consolidate CDF study results into maintainable documents.
3. Estimate more precisely the split between recurring and non-recurring costs and how the project can maximise economies of scale and re-use.
4. Begin a detailed platform design to support the instrument and spacecraft subsystems (would be a part of Phase A and B activities).

Appendix A: Abbreviations and Acronyms

Table 21: Abbreviations and acronyms

Abbreviation	Description / meaning
ACT	Australian Capital Territory
ADCS	Attitude Determination and Control Subsystem
AGO	Australian Geospatial-Intelligence Organisation
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/	Australian Space Agency
ASD	Australian Signals Directorate
ASDC	Australian Space Discovery Centre
AUD	Australian Dollar
AUS	Australian
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'Etudes 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
EO	Earth Observation
EPS	Electrical Power Subsystem
EQM	Engineering Qualification Model
ESA	European Space Agency
FM	Flight Model
FOC	Full Operational Capability

Abbreviation	Description / meaning
FoV	Field of View
FTE	Full-Time Equivalent
FWHM	Full-width half maximum
FY	Fiscal Year
GA	Geoscience Australia
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
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
NEDL	Noise Equivalent Radiance Difference
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
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
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, Engineering and maths
STM	Structure and Thermal Model
SWIR	Short-Wave Infrared
T	Threshold (for requirements)
TBC	To Be Confirmed
TBD	To Be Determined

Abbreviation	Description / meaning
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
WRT	With Respect To

Appendix B: Study Participants

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

Table 22: List of People Involved in the Study

Organisation	Person	Role / contacted for
ANU / AITC	Rob Sharp	Optical payload specialist
ASA	Arvind Ramana	Earth Observation, Space Technology & Advanced Communications
CSIRO	Alex Held Adam Macleod Stephen Gensemer Tim Malthus Nick Carter Kimal Hiralall	AquaWatch Mission
Geoscience Australia	David Hudson Medhavy Thankappan	SCR programme
UNSW Canberra Space Australian National Concurrent Design Facility	Denis Naughton Lena Meyer Igor Dimitrijevic Anthony Kremor Sam Boland Jan-Christian Meyer Andrin Tomaschett Damith Wickramasinghe	Mission design and domain expertise
SmartSat CRC	Andrew Barton Allison Kealy	Research programme 2 coordination
University of Queensland	Stuart Phinn	Earth observation remote sensing expert
SatDek	Arnold Dekker	Inland water remote sensing expert
Curtin University	David Antoine	Ocean water remote sensing expert

Appendix C: Australian Hyperspectral Instrument Pathfinder

An Australian built hyperspectral sensor for a smallsat requires considerable research and development investment. The not inconsiderable associated cost and schedule risk is best managed through a scaled development program enabled through a series of pathfinder missions to demonstrate key scientific, technological and operational components.

At the highest level, a hyperspectral sensor comprises a detector, optical imaging system (telescope), command and control systems, and satellite support capabilities. Based on assessments of the Australian space sector the telescope appears within the capability of several Australian integration vendors today (optical components will still require overseas fabrication but are widely available from multiple sources).

There are a range of focal plane array (detector) solutions for this type of instrument. Inexpensive “machine vision” solutions require limited development but provide only basic performance. There are well established international vendors (e.g. Teledyne, Sofradir), but no Australian commercial vendor (although significant local development for infrared array technology has emerged in recent years). Inexpensive COTS camera systems are likely well suited to early-stage pathfinder developments, however larger generation systems addressing the stated goals of the AquaWatch program will require higher performance devices. These higher-grade solutions typically also require bespoke detector control electronics. The inclusion of on-board processing and in-flight Artificial Intelligence (AI) will likely present data latency challenges requiring bespoke control hardware/firmware to be developed and flight tested via a staged pathfinder program.

A staged pathfinder development program is well supported by the Australian local satellite platform and operational support industry ecosystems. A range of current generation platforms would allow agile and inexpensive flight verification of sub-components and first-generation sensor systems, while active symbiotic developments in this field would inform the design of more capable second and third generation pathfinder missions, providing the much-needed support framework to grow this emerging yet vibrant industry.

Following consultation with the AquaWatch mission, ANU OzFuel (a SWIR bushfire hazard mitigation sensor) and the Australia space industry two mature pathfinder concepts exist:

1) CyanoSat: a CubeSat pathfinder to demonstrate multispectral imaging.
2) CHICO: a smallsat pathfinder to demonstrate hyperspectral VNIR imaging.

Following these pathfinders a fully featured AquaWatch could likely be achieved with lower risk.

Figure 5 outlines the different missions:

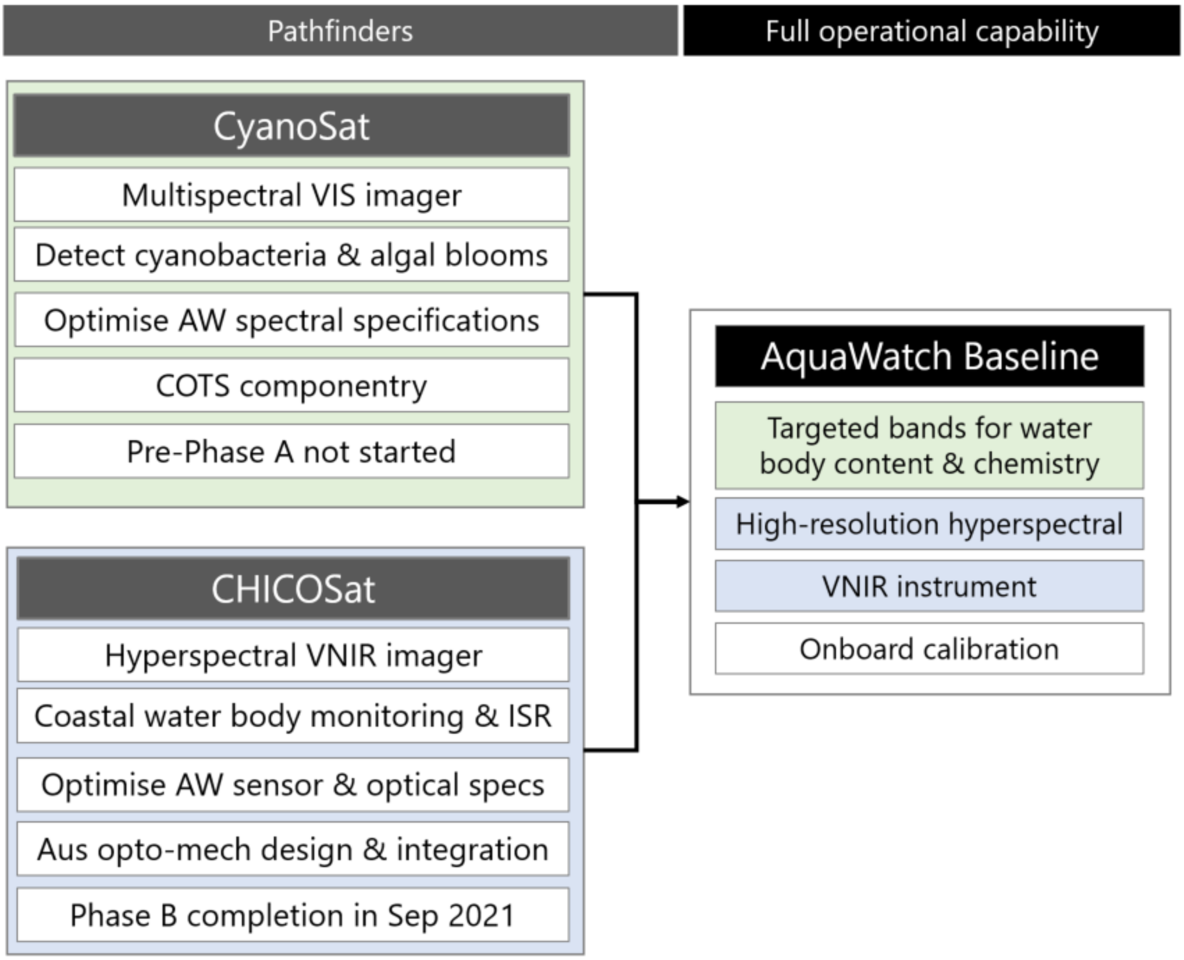

Figure 5: Technology pathfinders that aim to de-risk different sub-systems towards a fully operational AquaWatch Australia system

The “CyanoSat” pathfinder would be a CubeSat (or similar) featuring a multispectral cameral for detection of cyanobacteria and harmful algal blooms. This satellite would be a relatively simple design, with lower specifications than the planned AquaWatch satellites. By design it aims to deliver wide field observations at low ground resolution (GSD ~ 50-100 m), which simplifies demands on the satellite bus system attitude control and stability. It also requires lower data transmission rates. CyanoSat would prove the relationship between radiometric-resolution (brightness & dynamic range) and spatial and spectral resolution and provide excellent assistance in optimising the AquaWatch satellite design.

CyanoSat would also demonstrate a vertically integrated and operational system, including downlink, data processing and data archiving. Additionally, it would provide valuable data supporting early science, and have an immediate impact on management of water resources in Australia.

The “CHICOSat” pathfinder would be a 12U-CubeSat (or larger) that would provide flight heritage to the CHICO (CubeSat Hyperspectral Imager for the Coastal Ocean) instrument; a hyperspectral camera designed by the ANU, in partnership with DMTC, CSIRO and Skykraft.

This precursor project would verify the CHICO instrument against specifications similar to AquaWatch but developed in tandem with Defence and other user groups. In doing so it will provide significant TRL boosts to local capabilities in space-ready hyperspectral camera design & construction. It delivers GSD ~ 20-30 m, at the expense of added complexity of design with respect to the CyanoSat pathfinder.

CHICOSat would also:

- Complement development of simulations and models of system performance;
- Improve the GSD resolution, providing access to smaller inland water bodies;

- Provide hyperspectral capabilities, allowing tuneable post processing for multiple end user applications.

The specific technological challenges being explored by the CyanoSat and CHICOSat pathfinders on a pathway to a VNIR pan-hyperspectral system that has simple detector cooling requirements, broad user appeal with a wide range of cross calibration data opportunities are as follows:

- TDI-like operations (not reliant on forward motion compensation due to CubeSat ADCS performance limitations);
- Modest ground resolution (GSD ~ 20-50 m);
- Pre-flight and vicarious calibration baseline (provides laboratory platform for inflight calibration system development).

Development timeline:

- First quasi-COTS components integration tests (in orbit)
  - 6-12 months
- Locally derived component testing
  - 12-36 months Rolling test program for component development
- Multi-spectral camera (low GSD) orbital operations
  - 18-months
- Hyperspectral camera
  - 24-30 months

Lessons learned:

- Quasi-COTS options at TRL9 for local adoption at cost (i.e., development risk mitigated)
- Concentrate on the valuable end user products (e.g., AI data analysis in flight) and not the research/technology development sink of e.g., detector control systems.
- In flight experience with sensor system element of NASA/ESA/JAXA et al. grade, missions (e.g., Teledyne MCT VNIR arrays) rather than "machine vision grade" technology.

Development of a sustainable sovereign Australian industry capable of designing, building, and deploying powerful sensor system for remote sensing in the modern era, will require a scalable interdisciplinary collaboration between industry and research/technology innovators. Lessons learned from these pathfinders could then be used by Australian companies to deliver operational missions like SCR, AquaWatch Australia and OzFuel. ROM costs are included in Table 23 and Table 24 below.

Table 23: ROM cost estimate for a single CyanoSat mission

Element	Cost without any margin	Margin (locally applied)	ROM cost
CyanoSat Mission	**AUD 4.75 M**	**20%**	**AUD 7.7 M**
Ground Segment	AUD 0.2 M	0%	AUD 0.2 M
Launcher	AUD 1 M	10%	AUD 1.1 M
Mission Operations Centre	AUD 0.5 M	0%	AUD 0.5 M
Processing pipeline	AUD 0.25 M	100%	AUD 0.5 M
CyanoSat Satellite	AUD 4.8 M	0%	AUD 6.1 M
Environmental Qualification	AUD 0.2 M	50%	AUD 0.3 M
Integration + System-level Tests	AUD 0.2 M	0%	AUD 0.2 M

Payload	AUD 1.4 M	30%	AUD 1.8 M
Platform / Bus	AUD 1 M	0%	AUD 1 M

Table 24: ROM cost estimate for a single CHICOSat mission

Element	Cost without any margin	Margin (locally applied)	ROM cost
CHICOSat Mission	**AUD 6.3 M**	**20%**	**AUD 9.15 M**
Ground Segment	AUD 0.4 M	50%	AUD 0.6 M
Launcher	AUD 1 M	10%	AUD 1.1 M
Mission Operations Centre	AUD 0.5 M	50%	AUD 0.75 M
Processing pipeline	AUD 0.3 M	100%	AUD 0.6 M
CHICOSat Satellite	AUD 6.9 M	0%	AUD 9.6 M
Environmental Qualification	AUD 0.2 M	50%	AUD 0.3 M
Integration + System-level Tests	AUD 0.4 M	20%	AUD 0.5 M
Payload	AUD 2.5 M	30%	AUD 3.3 M
Platform / Bus	AUD 1 M	100%	AUD 2 M

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