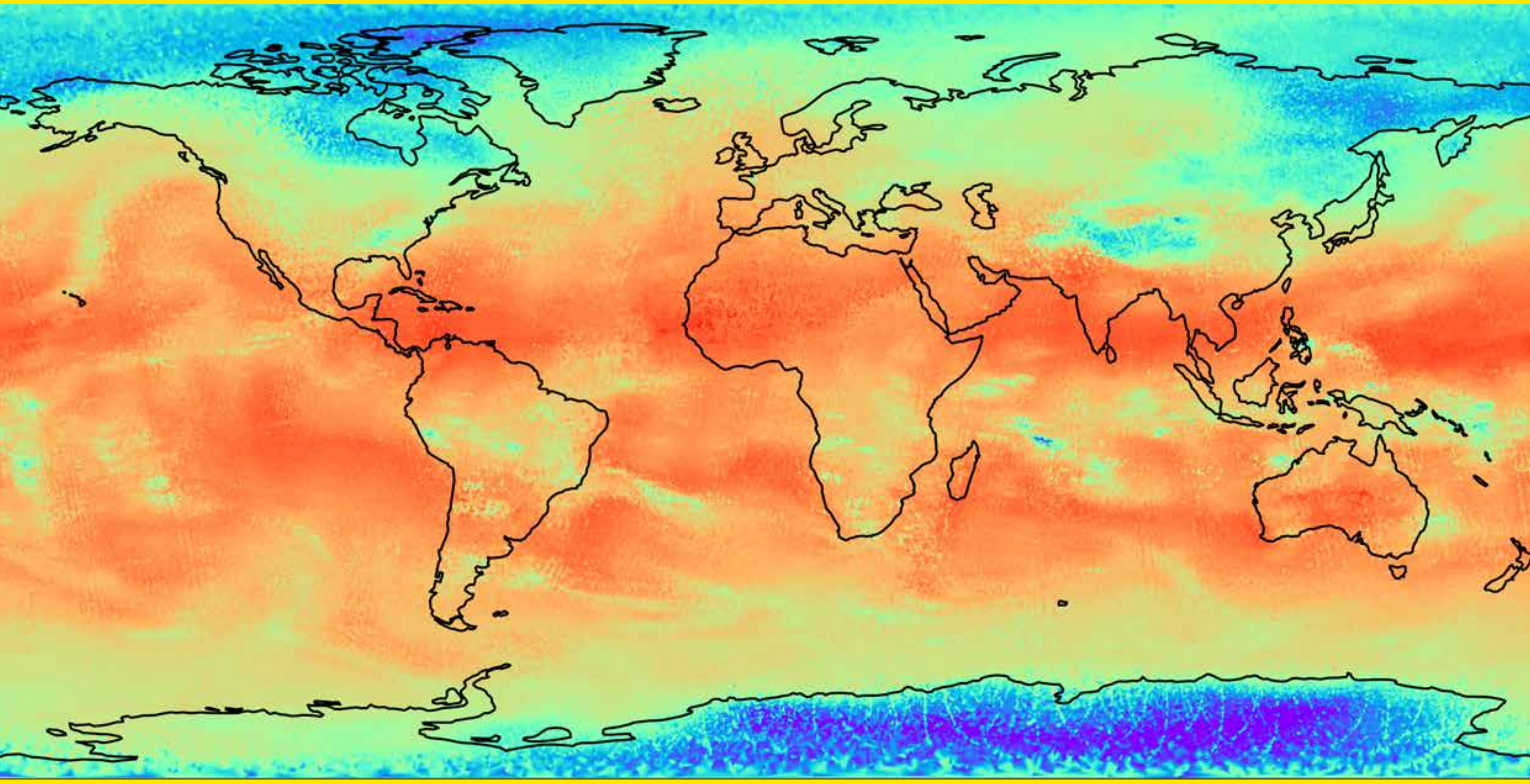
Australian-Developed Hyperspectral Microwave Sounder Pathfinder Mission to Support Global Temperature and Humidity Monitoring

Pre-Phase A Study



Australian National Concurrent Design Facility

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Cover image | Global temperature map generated using ATMS data processed by the Bureau of Meteorology.

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Australian National
Concurrent Design Facility

Pre-Phase A Study

Australian-Developed Hyperspectral Microwave Sounder Mission Pathfinder to Support Global Temperature and Humidity Monitoring

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Executive Summary

- This work reports on the **Microwave Sounder Mission Pathfinder** (MSM-PF) Pre-Phase A Study and subsequent work completed at the **Australian National Concurrent Design Facility** (ANCDF) by **UNSW Canberra Space** on the 11 – 14th October 2022 in Canberra, Australia, on behalf of and for the **Bureau of Meteorology**. From October 2022 to February 2023, **28 experts from 8 organisations** contributed to this study.
- The MSM-PF mission described in this report proposes to develop in Australia and fly a novel **passive hyperspectral microwave sounder**, enabling excellent noise performance, with a large number of channels (> 1000), over a wide spectral range. This mission is a **fully capable** precursor to an envisioned **MSM constellation** that would enable a high temporal resolution and low latency data provision, greatly benefiting the accuracy of global and local numerical weather prediction. The proposed instrument specifications are presented below.

Parameter	Value
Spectral bands	Temperature and humidity: 50-70 GHz, 183 GHz
	Tropical cyclone applications: 90 GHz, 118 GHz, 150GHz
	Climate monitoring and surface analysis applications: 19 GHz, 23.8 GHz, 31.4 GHz, 36-7 GHz
Number of channels	Approximately 1800 (digitally tuneable)
Noise level (NEΔT)	≤ 0.5 * ATMS instrument actual noise level
Spatial resolution	10 km at nadir
Swath width	1,950 km

- An Australian MSM constellation would **contribute in many ways to the national and international interests** by benefiting the global population through more accurate weather forecasts, stimulating and fostering the local industry, creating crucial international partnerships and encouraging technology transfer, positioning Australia as a key player in the global satellite weather observing networks, and increasing Australia's data sovereignty and resiliency.

- A conceptual payload design has been developed during the study, and it is found that a concept meeting most "Objective" user requirements (the highest specifications) is technically **feasible**. A platform conceptual design was also developed. The table below highlights key mission parameters.

Specification	Value	Unit
Operational mission life	3	years
Orbit type	Sun-synchronous, 05:30 equatorial crossing time	-
Orbit altitude	605.5	km
Spacecraft wet mass	169.5	kg
Spacecraft size	~ 74 x 74 x 74	cm^3
Orbit average power	181	W
Yearly data volume	8	TB

- This study assesses that **a fully capable MSM-PF mission will cost approximately $47M for a commercial bus implementation and approximately $64M for a bespoke bus implementation**, including payload development, dedicated launch, operations, commercial ground stations and data storage access. These costs can be reduced by launching on a rideshare or descoping the pathfinder to a lower specification. A **five-year schedule** to the end of commissioning was developed, positioning the pathfinder capability to be ready **by the end of the decade** if funding is approved.
- This study found that **research and development are required** on the proposed novel payload before an operational constellation capability is achieved. Several pathways leading to the envisioned MSM constellation were identified, of which the MSM-PF is one option (this report). Other options were a ground demonstrator, a CubeSat pathfinder and adapting an existing instrument currently in storage in the USA (SSMIS).
- **Frontier SI** has produced an independent assessment of the Australian space industry readiness for this mission and is delivered separately in a standalone report.

Document revision status

Date	Rev.	Status	Comments
03/03/2023	01	Released / unpublished	- First release.
21/04/2023	02	Released / unpublished	- Reorganised the introductory section. - Minor edits to clarify some statements. - Minor formatting.
30/05/2024	03	Released / Published	- Minor correction of instrument noise performance in Table 14 and Appendix D (from meeting objective to threshold requirement for MSM-USR-06-T), as well as updated comment in Table 6 (Channel Frequency specification column). - Minor edits to clarify some statements (sections 4.1 and 7.5).

Study Sponsors

The Bureau of Meteorology

Australian Space Agency

Above-the-line advice

Arizona State University

AEROSPACE

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Reference documents

All links have been accessed and are valid as of 27/02/2023.

[RD-01] Earth Observation from Space Roadmap. Australian Space Agency. Available at:

https://www.industry.gov.au/sites/default/files/January%202022/document/advancing_space_earth_observation_from_space_roadmap_2021-20303.pdf

[RD-02] Australian Bureau of Meteorology Pre-Phase A Mission Study Report. UNSW Canberra Space (2020). Available at:

https://www.unsw.adfa.edu.au/sites/default/files/documents/Australian_Bureau_of_Meteorology_Pre-Phase_A_Mission_Study_Report_0.pdf

[RD-03] Microwave Sounding Mission (MSM) Requirements. Bureau of Meteorology (2022). Unpublished.

[RD-04] Microwave Sounder Mission – Australian Workforce Capability Assessment. Pre-Phase A Studies for Australian-developed Satellite Missions for the Bureau of Meteorology. FrontierSI.

Contents

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List of Acronyms and Abbreviations

Acronym	Description/meaning
ACMA	Australian Communications and Media Authority
ACT	Australian Capital Territory
ADC	Analog-Digital Converter
ADCS	Attitude determination and control subsystem
AIT	Assembly, Integration, and Test
ANCDF	Australian National Concurrent Design Facility
ANGSTT	Australian National Ground Segment Technical Team
ANU	Australian National University
APE	Absolute Pointing Error
APEC	Asia-Pacific Economic Cooperation
APK	Absolute Pointing Knowledge
ASIC	Application-Specific Integrated Circuit
ASU	Arizona State University
ATMS	Advanced Technology Microwave Sounder
AUD	Australian Dollar
AUS	Australian
AWS	Amazon Web Services
CC BY	Creative Commons, Attribution
CEOS	Committee on Earth Observation Satellites
CLARREO	Climate Absolute Radiance and Refractivity Observatory
CMA	Chinese Meteorological Administration
CMP	Configuration Management Plan
CNES	Centre National d'Etudes Spatiales
CoM	Centre of Mass
COTS	Commercial Off-the-Shelf
CRC	Cooperative Research Centre
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CSS	Coarse Sun Sensor
DDVP	Design, Development and Verification Plan
DPAS	Data Processing and Archiving System
DSB	Double Sideband
EE	Electrical Engineer
EHS	Earth Horizon sensor
EM	Engineering Model
EMC	Electromagnetic Compatibility
EMI	Electromagnetic Interference
EO	Earth Observation
EPS	Electrical Power Subsystem
ESA	European Space Agency
ESD	Electro-Static Discharge
FEE	Front End Electronics
FM	Flight Model

FMC	Fuel Moisture Content
FPA	Focal Plane Array
FPGA	Field Programmable Gate Array
FPS	Frames Per Second
FRR	Flight Readiness Review
FTE	Full-Time Equivalent
FTS	Fourier Transform Spectrometer
GA	Geoscience Australia
GDP	Gross Domestic Product
GPS	Global Positioning System
GS	Ground Station or Ground Segment
GSD	Ground Sampling Distance
GSE	Ground Support Equipment
ICD	Interface Control Document
IF	Intermediate Frequency
IFOV	Instantaneous Field Of View
IR	Infrared
IRF	Impulse Response Function
Isp	Specific impulse
LEO	Low Earth Orbit
LEOP	Launch and Early Orbit Phase
LNA	Low Noise Amplifier
LO	Local Oscillator
LOS	Line Of Sight
LSP	Launch Service Provider
LTAN	Local Time of Ascending Node
LV	Launch Vehicle
MCR	Mission Concept Review
MOC	Mission Operations Centre
MSM	Microwave Sounder Mission
MSM-PF	Microwave Sounder Mission Pathfinder
MWS	Microwave Sounder (instrument)
N/A	Not Applicable
NASA	National Aeronautics and Space Administration
NEdL/NEΔT	Noise Equivalent change in radiance
NOAA	National Oceanic and Atmospheric Administration
NRE	Non-Recurring Engineering (costs)
NSTF	National Space Test Facility
NVM	Non-Volatile Memory
NWP	Numerical Weather Prediction
OBC	On-board computer
OE	Optical Engineer
PDR	Preliminary Design Review
PF	Pathfinder
PI	Principal Investigator
PICS	Pseudo Invariant Calibration Sites

PL	Payload
PM	Project Manager
PMM	Payload Management Module
R&D	Research & Development
RF	Radiofrequency
RFI	Radiofrequency Interference
RMP	Risk Management Plan
ROI	Region Of Interest
ROM	Rough Order of Magnitude
S/C	Spacecraft
SCR	Satellite Cross-calibration Radiometer
SE	System Engineer
SEMP	System Engineering Management Plan
SI	Systeme International
SM	Structural Model
SNR	Signal-to-Noise Ratio
SRR	System Requirements Review
SSB	Single Sideband
SSMIS	Special Sensor Microwave Imager/Sounder
SSO	Sun-Synchronous Orbit
STM	Structure and Thermal Model
TBC	To Be Confirmed
TBD	To Be Determined
TC	Tropical Cyclone
TDI	Time Delay Integration
TE	Thermal Engineer
TheMIS	Thermal Management Integrated System
TM	Thermal Model
TOA	Top Of Atmosphere
TRL	Technology Readiness Level
TT&C	Telemetry, Tracking, and Command
UK	United Kingdom
UNSW	University of New South Wales
US	United States
USD	US Dollar
USGS	United States Geological Survey
WBS	Work Breakdown Structure
WIGOS	WMO Integrated Global Observing System
WMO	World Meteorological Organization
WMO ET-SSU	WMO Expert Team on Space Systems and Utilization

1 Introduction

1.1 Document purpose and scope

This document reports on the Microwave Sounding Mission Pathfinder (MSM-PF) study at the Australian National Concurrent Design Facility (ANCDF) by UNSW Canberra Space on the 11 – 14th October 2022 in Canberra, Australia, and subsequent work completed on behalf and for the Australian Bureau of Meteorology (the Bureau). From October 2022 to February 2023, a total of 28 experts from 8 organisations contributed to this study.

The MSM-PF is a microwave sounding mission envisioned as the precursor to a future constellation of microwave sounders referred to as the Microwave Sounder Mission (MSM) constellation.

Section 1 (this section) contextualises the study and provides background information on the ANCDF. It concludes by presenting the FrontierSI associated report and a disambiguation section.

Section 2 presents the mission objectives and the programmatic and end-user requirements of the MSM mission. *This information is based on customer-supplied requirements.*

Section 3 provides an introduction to microwave sounding, a survey of the current art and exposes a rationale for an Australian-developed Microwave Sounder Mission. It then exposes the identified pathways to achieve an operational MSM constellation.

Section 4 gives an overview of the proposed space segment and its concept of operations. It then proceeds to orbit selection and provides some constellation examples.

Section 5 explores payload design options and presents a preliminary payload sizing (size, weight, power and data rate) that informs the platform design presented in section 6.

Section 6 delves into the platform's subsystems' preliminary design based on information from sections 4 and 5.

Section 7 assesses implementation options for the various elements of the space segment, including the platform, ground activities and launch.

Section 8 proposes a mission schedule and provides a costing estimate of the MSM-PF mission.

Section 9 concludes the report with recommendations for future work and analyses of the proposed mission.

Appendices provides details on some derivations and a summary of the derived requirements and specifications for the MSM-PF.

1.2 Study context

The Bureau has been a substantial user of Earth observations from space for several decades, and this continues to grow at a significant pace. The Bureau currently assimilates data from over 30 satellites into weather, ocean and hydrology prediction and visualisation systems every day. This is crucial for the provision of weather forecasts and warnings across Australia and beyond to support national Bureau commitments for safety and security.

Australia does not own or operate Earth Observation (EO) meteorological satellites and relies on foreign-owned satellites for these observations. Developing a sovereign Australian EO satellite capability would assist in guaranteeing long-term access to meteorological observations from space and in reducing the risk of losing free and open access to critical satellite data streams required for weather forecasting.

In the 2021 Earth Observation Roadmap [RD-01] developed by the Australian Space Agency (ASA), the Bureau articulated an ambition for Australian operational meteorological satellite sensing capabilities in the 2030s. To achieve this ambition, the Bureau commissioned UNSW Canberra Space in 2021 to undertake in the Australian National Concurrent Design Facility (ANCDF, presented in the next section) a preliminary investigation into satellite mission pathfinders to build towards this capability.

The resulting Pre-Phase A Mission Study Report [RD-02] identified three missions for further exploration that can support the Bureau's goals in meteorological forecasting and disaster monitoring and mitigation:

- A Synthetic Aperture Radar (SAR) Mission
- A Hyperspectral Microwave Sounder Mission (MSM)
- A Lightning Detector Mission (LD).

To further analyse potential mission implementations to meet the Bureau's requirements, the ANCDF was engaged again in 2022 to conduct three follow-on Pre-Phase A on these missions.

<u>The study reported on in this document further refines and develops the concept of an Australian-developed Hyperspectral Microwave Sounding Mission Pathfinder.</u>

The Bureau's MSM mission is envisioned as a constellation of small satellites in the 170 kg-class that would cater for an important part of numerical weather prediction data needs. As such, this mission fully fits the Bureau's ambition for an Australian operational meteorological satellite sensing capability in the 2030s, as outlined in the EO Roadmap [RD-01].

It is to be noted that funding approval for the MSM-PF and MSM constellation is yet to be secured.

1.3 The Australian National Concurrent Design Facility

The Australian National Concurrent Design Facility (ANCDF) is a national asset that UNSW Canberra Space operates for feasibility studies and preliminary design of space missions. It is available to support Australian space programme development based on concurrent engineering methodology. The facility was established in 2017 under an Australian Capital Territory (ACT) government grant and in partnership with the French Space Agency (CNES). It has been conceived for rapid assessment and conceptual design of future Australian space missions (i.e., pre-Phase A to Phase A studies, following NASA's definitions of mission phases[1]).

The facility features a team-oriented concurrent engineering process with the support of integrated tools, project data, mission and system models, and simultaneous participation of all mission domain experts, including Operations, Programmatic/AIT, Technical Budgets, Cost Engineering, Risk Analysis, Simulations, as well as the customer. The software engine that underpins it, derived from the French Space Agency, CNES, and further developed by UNSW Canberra Space, enables best practice concurrent engineering design and analyses.

The design process is collaborative and iterative, allowing open discussion between all participants regarding the mission requirements and objectives, cost and schedule constraints, design options and trade-offs. This allows mission implementation options to be assessed and adjusted to better meet customer needs.

Figure 1: The Australian National Concurrent Design Facility (credit: Pew Pew Studio).

The typical final product of the ANCDF process is a comprehensive study report (such as this one) that details the overall mission concept, including spacecraft design and configuration, launch options, risk, cost and schedule analyses, and can consider alternative options and trade-offs. This enables the customer to make informed decisions regarding specific mission design and implementation of choices for the requirements and design phases of the programme.

Over two dozen studies have been conducted, including work with Airbus, the French Space Agency CNES, the Office of National Intelligence, the Australian Space Agency, Geoscience Australia, CSIRO and the Bureau of Meteorology. In particular, the ANCDF housed the pre-phase-A and Phase A studies for Geoscience Australia's Satellite Cross-calibration Radiometer (SCR) and Multi-Mission Imager (MMI), CSIRO's AquaWatch mission and ANU's OzFuel mission.

1.4 FrontierSI Australian industry capability and readiness assessment

This report is accompanied by an Australian industry capability and readiness assessment conducted by Frontier SI [RD-04]. The assessment focuses on the implementation aspects of the MSM-PF mission and, more particularly, the availability and readiness of Australian capabilities, facilities and know-how to develop this mission, including all segments – space, user, ground and launch segments. Frontier SI's report is delivered as a standalone document.

1.5 Disambiguation

This work reports on the Microwave Sounding Mission Pathfinder (MSM-PF) spacecraft concept, the precursor to the envisioned operational Microwave Sounding Mission (MSM) constellation.

The MSM-PF will be a pathfinder to the MSM constellation in a sense that:

- It is not required to achieve an operational capability in terms of data timeliness (except for local Australian data), temporal resolution (which only a constellation can achieve) and final orbit placement.
- It will be used to refine the MSM concept, increase technology readiness levels and de-risk the program as a whole.
- It aims to fly in space one of the first hyperspectral microwave sounders, a type of instrument that has not been flown to date, which therefore requires some level of technology development.
- It will be an Australian-developed small satellite, a class of spacecraft not yet launched by the Australian space industry.

The MSM-PF, particularly its payload, will be designed as similarly as possible to the final MSM satellites. In that sense, it is a fully capable pathfinder to the MSM. The other mission segments, such as the user and ground segment, will be re-used and expanded to the possible extent when the program transitions from the MSM-PF to the operational MSM constellation.

2 Mission Requirements

This section presents a mission objective statement alongside the mission's programmatic and user requirements. **The information compiled in this section has been transferred from a pre-study document supplied by the Bureau [RD-03].** It is reproduced here as is for completeness, as these are the requirements the ANCDF team used to develop the mission concept proposed in this report.

2.1 Mission objectives

2.1.1 Mission aim

A mission aim or objective statement describes what a mission aims to achieve at the highest level.

> **The aim of the Microwave Sounding Mission is to provide high-quality microwave-sounding measurements of the atmosphere with global coverage and sub-daily revisit in the Australian region and adjacent Antarctic territory to address Bureau customer needs for increasingly accurate numerical predictions and severe weather monitoring capability.**

2.1.2 Primary mission objectives

Table 1 presents the MSM's primary mission objectives *as communicated by the Bureau*. These are key measures of success for this mission.

Table 1: MSM primary mission objectives (source: Bureau of Meteorology).

ID	Objective
MSM-OBJ-01	To support Bureau of Meteorology numerical weather prediction at regional and global scales with temperature and humidity sounding information at 50-60 GHz and 183 GHz respectively, with radiometric noise not greater than the ATMS instrument.
MSM-OBJ-02	To support Bureau of Meteorology Tropical Cyclone and severe precipitation applications with observations at 89-90 GHz, with radiometric noise not greater than the ATMS instrument.
MSM-OBJ-03	To support next-generation numerical weather prediction with improvements in vertical resolution of the measurements and enhanced mitigation against radio frequency interference (RFI) via provision of higher spectral-resolution information than the MWS instrument in the main frequency ranges of interest.
MSM-OBJ-04	To develop microwave instrumentation that delivers improvements in one or more of the following areas: ▪ Better spatial resolution than the MWS instrument in support of tropical cyclone monitoring and high-resolution numerical weather prediction; ▪ A breakthrough improvement in radiometric performance; ▪ Better Size Weight and Power for Cost (SWaP-C) than microwave sounders currently flying or approaching launch, facilitating the development of a constellation mission in support of rapid-update data assimilation and tropical cyclone monitoring.

2.1.3 Secondary mission objectives

Table 2 presents the MSM secondary mission objectives *as communicated by the Bureau*. These are secondary measures of success for this mission.

Table 2: MSM secondary mission objectives (source: Bureau of Meteorology).

ID	Objective
MSM-OBJ-05	To provide measurements that support detection, monitoring and forecasting of precipitation including one or more of the following: ▪ Contributing to more frequent measurements that allow the detection of hydrometeors and precipitation; ▪ Increased vertical information content for cloud liquid water and water vapour, especially in the boundary layer; ▪ Including frequencies below 50 GHz that allow better characterisation of precipitation.
MSM-OBJ-06	To provide measurements at frequencies below 50 GHz that support land, sea and ice-surface applications, including windspeed, surface temperature and surface emissivity.
MSM-OBJ-07	To build international partnerships to facilitate the development of a joint constellation mission, reducing risk, improving collaboration opportunities, and creating international interest in the mission.
MSM-OBJ-08	To develop an instrument that fits a standard bus, creating opportunities for hosted payloads, ride-share and other launch options.
MSM-OBJ-09	To provide measurements that either: ▪ Fill a gap in the global observing system, enabling Australia to contribute in a meaningful way to core observations under WIGOS ▪ Increase the temporal coverage of standard frequency microwave observations, providing additional sounding data that will benefit global numerical weather prediction and worldwide severe weather monitoring
MSM-OBJ-10	To provide polar coverage to support the Bureau's Antarctic modelling and climate change research.

2.2 Programmatic requirements

Table 3 presents the MSM programmatic requirements *as communicated by the Bureau*. These are non-technical, program-level constraints.

Table 3: MSM programmatic requirements (source: Bureau of Meteorology).

ID	Requirement
MSM-PRG-01	The mission shall deliver capability into the Australian space industry.
MSM-PRG-02	The mission shall store all data from the mission in Australia and make it available from the data hub.
MSM-PRG-03	The mission shall consider the possibility of locating the Mission Operations Centre (MOC) and its staff in Australia or sharing the MOC with an international partner.
MSM-PRG-04	The mission shall adhere to Australian policies and industry best practices in areas including, but not limited to: security, privacy, data policy, interoperability and responsible use of space.
MSM-PRG-05	The mission data, products and services shall be made freely available.
MSM-PRG-06	The mission shall leverage existing National Space Program and Sub-Program governance, procurement strategy and ground segment wherever viable.
MSM-PRG-07	The mission budget is $30-60M.
MSM-PRG-08	The mission shall align with the Bureau's strategy.
MSM-PRG-09	The mission shall undergo space segment Assembly, Integration and Testing in Australia as far as possible.
MSM-PRG-10	The pathfinder mission shall complete in-orbit commissioning within 4-5 years of the kick-off of the implementation phase.

2.3 End-user requirements

Table 4 summarises the MSM end-user requirements *as communicated by the Bureau*. These are specific end-user scientific, technical, and functional requirements to meet the mission's scientific objectives. The requirements are divided into three categories, namely:

- Threshold: Minimum performance required to meet the end-users' needs.
- Breakthrough: Performance that will enable the instrument to provide new services or an appreciable step up in performance compared to existing capabilities.
- Objective: The goal; this performance level may or may not be attainable in conjunction with other requirements, but it indicates what users want.

Table 4: MSM end-user requirements (source: Bureau of Meteorology).

ID	Parameter	Objective-O	Breakthrough-B	Threshold-T
MSM-USR-01	Spectral Bands	50-70 GHz, 90 GHz, 183 GHz, Plus: 118 GHz, 150GHz Plus: 31.4 GHz,36-7 GHz, 23.8 GHz, 19 GHz OR: Complete spectral coverage between 19 and 183 GHz	50-60 GHz, 90 GHz, 183 GHz, Plus: 118 GHz, 150 GHz	50-60 GHz, 90 GHz, 183 GHz
MSM-USR-02	Number of channels	Approx. 1800	Approx. 1100	Approx. 400
MSM-USR-03	Spectral resolution v /Δv	5000 (T) 4575 (WV)	2500 (T) 1830 (WV)	1250 (T) 915 (WV)
MSM-USR-04	Spatial Coverage	Global	Global	Full coverage of Australia, including its surrounding area
MSM-USR-05	Swath width	>=2200 km (tied to orbit height and viewing geometry)	>=2052 km (tied to orbit height and viewing geometry)	>=1800 km (tied to orbit height and viewing geometry)
MSM-USR-06	Noise Level (NEΔT)	≤ ATMS actual * 0.5 for spectrum integrated to ATMS SRF and IFOV	≤ ATMS actual * 0.66 for spectrum integrated to ATMS SRF and IFOV	≤ ATMS actual for spectrum integrated to ATMS SRF and IFOV
MSM-USR-07	Spatial resolution (footprint)	≤5 km at nadir	≤15 km at nadir for temperature sounding. ≤7 km at nadir for humidity.	≤25 km at nadir for temperature sounding. ≤15 km at nadir for humidity.
MSM-USR-08	Geolocation accuracy	≤10% spatial resolution	≤ 17% spatial resolution	≤25 % spatial resolution
MSM-USR-09	Viewing Geometry	Up to +/-55°, multiple view angles per ground footprint	Up to +/-55°	Up to +/-55°

ID	Parameter	Objective-O	Breakthrough-B	Threshold-T
MSM-USR-10	Polarization	Low-frequency channels (≤37 GHz) polarised	Single linear polarization changing with scan angle (as ATMS)	Single linear polarization changing with scan angle (as ATMS)
MSM-USR-11	Spatial sampling	Oversampling (Nyquist at minimum)	Contiguous Footprints	Non-contiguous
MSM-USR-12	Calibration mechanism	2-point calibration -40 to -50 dB return loss from onboard source	2-point calibration -40 to -50 dB return loss from onboard source	2-point calibration
MSM-USR-13	Calibration accuracy	≤0.2 K	≤0.5 K	≤1 K
MSM-USR-14	Temporal Refresh	Sub-hourly	≤Every 3 hours	≤Every 6 hours *for single pathfinder, once every 12 hours is acceptable*
MSM-USR-15	Instrument lifetime	7 years	5 years	3 years *for a single pathfinder, a 2-year lifetime is acceptable*
MSM-USR-16	Data timeliness	90% within 1 hour	90% within 2 hours	NRT - 90% within 3 hours 30 mins *for single pathfinder, there is no NRT timeliness requirement*
MSM-USR-17	Local data timeliness	90% within 10 mins	90% within 15 mins	90% within 20 mins

3 Mission Justification

3.1 Introduction to microwave sounding

3.1.1 Principles

A passive microwave sounder primarily aims to provide vertical profile information on atmospheric temperature and humidity. An extended spectrum of sensed frequencies can provide additional information on total column water vapour and precipitable water burden, as well as detection and possibly quantification of precipitation.

By nature, the measurement of these quantities is indirect. Gases in the atmosphere emit radiation at different frequencies. The microwave sounder records the top-of-atmosphere radiance measurements at specific frequencies (or channels) that correspond to the emission frequencies of oxygen (for temperature sounding) and water vapour (for humidity sounding). Information on the atmospheric profile can be extracted from the sounder observations by combining multiple channels, using a radiative transfer model to map between the atmospheric state and the measurement space. This is the subject of considerable research activity.

3.1.2 Applications

Space-based microwave sounders produce one of the most important sets of observations supporting numerical weather prediction[2] (NWP), with their impact expected to increase in future decades. A study[3] suggested that microwave sounders contribute about 45% of the positive impact of all satellite observations in global NWP. They provide great benefits to society as a whole through several applications:

- **Weather forecasting:** The main application of microwave sounding data is weather forecasting via NWP. NWP requires observations to be made at 50-60 GHz for temperature and 183 GHz for humidity, while additional frequencies provide supplementary information and enable quality control.
- **Precipitation detection and quantification:** Although mostly insensitive to clouds, some microwave frequencies are scattered by precipitation, which enables microwave sounders to significantly contribute to the global precipitation observing system. Precipitation applications require observations at 89-90 GHz and 37 GHz if available. Quantification of snowfall using the 89-90 GHz channels is essential for weather observing and long-term climate analysis in the Australian Antarctic Territory and contributes to sea ice modelling.
- **Tropical cyclone detection, monitoring and nowcasting:** Microwave sounders complement wind field observations by scatterometers which are impeded by the rainfall and small islands typically observed near tropical cyclones (TC). Along with the 50-60 GHz channels for temperature sounding, TC applications require the 89-90 GHz channels for precipitation detection. There is some evidence[4] that the 118 GHz temperature sounding channels are useful for TC applications.

- **Climate monitoring:** The continuous nature and long historical record of microwave sounding observations mean that they form an important part of the global climate data records, thus enabling climate monitoring and trend studies to be conducted. Climate applications require excellent noise and calibration stability performances and a long mission duration.
- **Surface analysis:** Microwave sounders can incorporate frequencies below 37 GHz. For NWP applications, these can be used for surface emissivity quantification and quality control. They can also be used directly for sea-ice quantification and characterisation. Additionally, dually polarised instruments can access additional information, such as wind speed in the lower frequencies.

Table 5 condenses the above information into a summary of applications along their required frequency channels.

Table 5: Summary of microwave sounding applications per sounding channel.

	< 37 GHz	37 GHz	50-60 GHz	89-90 GHz	183 GHz
Weather forecasting			✓		✓
Precipitation applications		✓		✓	
Tropical cyclone applications			✓	✓	
Climate monitoring	✓	✓	✓	✓	✓
Surface analysis	✓				

Weather forecasting is the primary application of most microwave sounding missions, and is a key focus of the Bureau's operations; therefore, the 50-60 GHz (temperature) and 183 GHz (humidity) channels must belong to the observed spectrum.

3.2 Rationale for an Australian-developed Microwave Sounder Mission

This section presents a rationale for an Australian-developed hyperspectral microwave sounder mission. First, section 3.2.1 exposes the current observational gap in microwave sounder data identified by the World Meteorological Organization (WMO). Then, section 3.2.2 presents a survey of related missions and shows that space-based hyperspectral microwave sounders have never been flown to date, thus identifying technological development opportunities and other mission benefits of an Australian MSM in section 3.2.3.

3.2.1 Current observational gap

The WMO, together with the Coordination Group for Meteorological Satellites (CGMS) undertake an annual review of the gaps in the global observing system that can be addressed with satellite data. CGMS High Level Priority Plan identifies areas where investment is needed most critically. At the present time, there are gaps identified in the global constellation of microwave sounders, and a need for more frequent observations.

The WMO Expert Team on Space Systems and Utilization (ET-SSU) identifies microwave radiances from "*core constellation satellites in three orbital planes (morning, afternoon, early morning)*" and "*Sun-synchronous satellites at three additional (any other than above) equatorial crossing times for improved robustness and improved time sampling*" as backbone data essential for global NWP[5].

The WMO Vision for the WMO Integrated Global Observing System (WIGOS) 2040[6], therefore, states a requirement for microwave sounding from 6 different sun-synchronous orbital planes, including the core constellation defined by the ET-SSU. WMO is expected to endorse High-Level Guidance for the evolution of WIGOS that proposes a move towards hourly microwave observations[*].

Concerning precipitation capability, WMO OSCAR-Space Gap Analysis (CGMS-50-WMO-WP-08)[7] identifies the following gap:

> Gap 06.2 - Frequent coverage requires many microwave radiometers operating on suitable frequency range (e.g., 10 to 90 GHz). Many are available, imagers and/or sounders. However, often the lowest frequency is not suitable for heavy liquid precipitation, the highest for solid, and the space resolution too coarse.

Providing data at 90 GHz and/or 37 GHz would help fill this gap, particularly if the spatial resolution is significantly better than the current instrumentation.

WMO OSCAR-Space Gap Analysis (CGMS-50-WMO-WP-08)[7] also identifies the following gap:

> *Gap 06.3 - The most important feature for hydrology is the Accumulated precipitation, that is accurately measured only if the sampling rate is in the range of few tens of minutes. IR GEO imagery is used, "calibrated" by co-located (infrequent) microwave measurements. This is acceptable only for convective precipitation. Microwave sounding is planned to be used by FY-4M.*

FY-4M, as referred to in this statement, is a GEO microwave sounder with unproven technology that would not provide global observations. A large constellation of LEO sounders, even if heterogeneous, could also meet this requirement, potentially more cheaply (as suggested by the costing in this study) and with the robustness of a many-instrument system. The MSM-PF could form part of such a constellation and enable an even more significant contribution to the international weather observing system when the MSM constellation is implemented.

[*] Personal communication of F. Smith, PI for the Bureau's MSM-PF.

3.2.2 Survey of related missions

3.2.2.1 Analogue spectrometer mission

Table 6 presents a non-comprehensive survey of some relevant past, current and future microwave spectrometers used for atmospheric sounding. It is proposed and justified in section 5.2 that the Bureau's MSM-PF is envisioned as a digital cross-track scanning microwave spectrometer. Note that to this day, no digital or hyperspectral spectrometer has been flown in space, although several projects are being developed (see next section). For consistency with the mission proposed in this report, only instruments sensing both temperature and humidity (like the Bureau's MSM) have been included. An important difference between the Bureau's MSM-PF and the other survey missions is the digital nature of the instrument's back-end, allowing it to measure many spectral channels.

Table 6: Survey of analogue microwave sounding instruments.

Specification	ATMS	AWS	BOWIE-M	EON-MW	MWS	SSMIS	MSM-PF*
Spacecraft							
First launch date	2011	Expected 2024	Not flown	Expected 2023	Expected 2025	2003	~2027-2028
Origin	USA	Europe	USA	USA	Europe	USA	Australia
Owner	NOAA	ESA/EUMETSAT	Ball Aerospace (developer)	NOAA	EUMETSAT	Air Force DMSP	Bureau of Meteorology
Spacecraft name	S-NPP, NOAA-20, NOAA-21	AWS-PFM	N/A Commercially developed instrument	EON-MW	Metop-SG-A1, Metop-SG-A2 and Metop-SG-A3	Past: DMSP-F16 and DMSP-F19 Current: DMSP-F17 and DMSP-F18	-
Spacecraft mass (kg)	> 1400	120	(SmallSat)	20	4000	1200	169.5
Payload							
Payload type	Analogue cross-track scanner	Analogue cross-track scanner	Analogue cross-track scanner	Analogue cross-track scanner	Analogue cross-track scanner	Analog conical scanner	Digital cross-track scanner
Payload Size (mm)	600 x 700 x 400	500 x 400 x 600 (est.)	660 x 390 x 440	220 x 220 x 340	1000 x 1430 x 522	700 x 700 x 950 (est.)	600 x 700 x 400
Payload Mass (kg)	75.4	42.1	35	4	132	96	50.5
Payload Power (W)	93	72.8	70	22.7	137	135	130.5

* The MSM-PF instrument's specifications are proposed and justified in section 5.

Specification	ATMS		AWS		BOWIE-M		EON-MW		MWS		SSMIS		MSM-PF*
Payload Data Rate (kbps)	20		64		<50		50		30		14.2		2024
Swath width (km)	2200		1860		2200		2200		2300		1700		1950 (orbit dependent)
Spatial resolution (km)	16 (165-183 GHz) / 32 (50-90 GHz) / 75 (23-32 GHz)		40 (50.3-57.3 GHz) / 20 (89 GHz) / 10 (165.5-325 GHz)		<25km @ 832km altitude (horizontal)		Unknown		17 (89-229 GHz) / 20 (50 - 58 GHz) / 40 (23.8 and 31.4 GHz)		17 (89-229 GHz) / 20 (50 - 58 GHz) / 40 (23.8 and 31.4 GHz)		10 (to be refined on a per channel basis)
No. Channels	22		19		22		22		24		24		1800
	Not sensed.										19.35	0.34	19
Channel Frequency (GHz) / NEΔT (K) *For the MSM-PF, NEΔT same as ATMS actual (MSM-USR-06-T)*	23.8	0.22	*Not sensed.*		23.8	0.55	23.8	0.7	23.8	0.25	22.23	0.45	23.8
	31.4	0.25			31.4	0.69	31.4	0.7	31.4	0.35	*Not sensed.*		31.4
	Not sensed.										37.0	0.24	36-37
	50.3	0.30	50.3	0.6	50.3	0.68	50.3	0.9	50.3	0.5	50.3	0.21	50-70
	51.76	0.22	52.8	0.4	51.76	0.45	51.76	0.7	52.8	0.35	52.8	0.20	
	52.8	0.22	53.246	0.4	52.8	0.45	52.8	0.7	53.24 ± 0.08	0.4	53.596	0.21	
	53.596 ± 0.115	0.24	53.596	0.4	53.596	0.55	53.596 ± 0.115	0.7	53.59 ± 0.115	0.4	54.4	0.20	
	54.4	0.22	54.4	0.4	54.4	0.47	54.4	0.7	53.94±0.081	0.4	55.5	0.22	
	54.94	0.22	54.94	0.4	54.94	0.50	54.94	0.7	54.4	0.35	57.29	0.26	
	55.5	0.22	55.5	0.5	55.5	0.54	55.5	0.7	54.94	0.35	59.4	0.25	
	f0 = 57.290344	0.30	57.290344	0.6	57.290344 (f0)	0.53	f0 = 57.290344	0.75	55.5	0.4	60.79 ± 0.35 ± 0.050	0.38	
	f0 ± 0.217	0.42			f0 ± 0.217	0.76	f0 ± 0.217	1	57.29	0.4	60.79 ± 0.35 ± 0.016	0.37	
	f0 ± 0.3222 ± 0.048	0.48			f0 ± 0.322 ± 0.048	0.76	f0 ± 0.3222 ± 0.048	1	57.29 ± 0.217	0.55	60.79 ± 0.35 ± 0.006	0.58	
	f0 ± 0.3222 ± 0.022	0.70			f0 ± 0.322 ± 0.022	1.08	f0 ± 0.3222 ± 0.022	1.5	57.29 ± 0.32±0.04	0.6	60.79 ± 0.35 ± 0.002	0.86	
	f0 ± 0.3222 ± 0.010	1.00			f0 ± 0.322 ± 0.010	1.51	f0 ± 0.3222 ± 0.010	2.4	57.29 ± 0.32±0.02	0.9	60.79 ± 0.35	1.18	
	f0 ± 0.3222 ± 0.0045	1.60			f0 ± 0.322 ± 0.004	2.49	f0 ± 0.3222 ± 0.0045	3.6	57.29 ± 0.32±0.01	1.2	63.28 ± 0.28	1.23	
									57.29 ± 0.32 ± 0.0045	2.0			

Specification	ATMS		AWS		BOWIE-M		EON-MW		MWS		SSMIS		MSM-PF*
	89.5	0.18	89	0.3	88.2	0.27	88.2	0.5	89	0.25	91.6	0.19	90
	Not sensed.												118
	Not sensed.										150	0.53	150
	165.5	0.32	165.5	0.6	165.5	0.36	165.5	0.6	164-167	0.5			*Not sensed.*
			176.311	0.7									
			178.311	0.7									
			180.311	1									
			181.311	1									
			182.311	1.3									
	183.31 ± 7.0	0.32			183.31 ± 7	0.37	183.31	0.9	183.31±7.0	0.4	183.31 ± 6.6	0.56	183
	183.31 ± 4.5	0.33			183.31 ± 4.5	0.39	185.31	0.8	183.311±4.5	0.4	183.31 ± 3.0	0.39	
	183.31 ± 3.0	0.38			183.31 ± 3	0.51	187.31	0.8	183.311±3.0	0.6	183.31 ± 1.0	0.38	
	183.31 ± 1.8	0.40			183.31 ± 1.8	0.49	189.31	0.8	183.311±1.8	0.6			
	183.31 ± 1.0	0.60			183.31 ± 1	0.61	191.31	0.8	183.311±1.0	0.75			
			325.15±1.2	1.7					229.0	0.70			*Not sensed.*
			325.15±2.4	1.4									
			325.15±4.1	1.2									
			325.15±6.6	1									

Not included in this survey are the following instruments:

- AMSU-A (NOAA), temperature sounding only
- AMSU-B (NOAA/EUMETSAT), humidity sounding only
- MHS (EUMETSAT), humidity sounding only
- MSU (NOAA), temperature sounding only
- MWTS-1, MWHS-1, MWTS-2, MWHS-2 (CMA), temperature and humidity soundingNEMS (NOAA), temperature sounding only
- SAPHIR (CNES), humidity sounding only
- CubeSat missions (except EON-MW due to its similarity with ATMS)

Microwave imagers (e.g., MWI or GMI), with the exception of SSMIS (due to the discussion in section 3.3.3), have not been included in this survey due to the design differences with spectrometers such as the MSM-PF.

Certainly, all these instruments, including those not included in the survey, provide heritage to microwave-sounding instrumentation and can be leveraged for the development of the MSM-PF and the MSM constellation.

References – *All links are valid as of 14/02/2023*

ATMS

- https://space.oscar.wmo.int/instruments/view/atms
- https://link.springer.com/chapter/10.1007/978-3-540-37293-6_13
- https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2013JD020483

AWS

- https://www.esa.int/Applications/Observing_the_Earth/Meteorological_missions/Arctic_Weather_Satellite/Facts_and_figures
- https://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=5087&context=smallsat

BOWIE-M

- https://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=4725&context=smallsat
- https://www.youtube.com/watch?v=Yj3IGaKDcj4

EON-MW

- https://www.tandfonline.com/doi/full/10.1080/16000870.2020.1857143
- https://www.researchgate.net/publication/347675024_A_preliminary_assessment_of_the_value_and_impact_of_multiple_configurations_of_constellations_of_EON-MW_a_proposed_12U_microwave_sounder_CubeSat_for_global_NWP
- https://digitalcommons.usu.edu/cgi/viewcontent.cgi?filename=0&article=3637&context=smallsat&type=additional

MWS

- https://www.eumetsat.int/eps-sg-microwave-sounder
- https://www.eumetsat.int/media/43204
- https://exchange.esa.int/download/thermal-workshop/workshop2017/parts/MWS.pdf

SSMIS

- https://space.oscar.wmo.int/instruments/view/ssmis
- https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=4475705

3.2.2.3 Digital/hyperspectral spectrometer missions

No hyperspectral microwave sounder mission has been launched to date.

The major development brought in by digital spectrometers compared to the traditional analogue spectrometers is the much larger number of spectral channels that can be observed (from a couple of dozens to potentially thousands), as well as the in-orbit tunability providing some level of flexibility to adjust these channels (for example to mitigate radio-frequency interference). Instruments of this category currently under development fall under three classes: airborne instruments, ground-based instruments and space instruments.

Airborne and ground-based instruments are typically simpler and less expensive to design, build and test than their space-based counterparts as there are typically fewer constraints on size, weight and power. Ground-based instrumentation is upward-looking and only able to sound the lower atmosphere due to the decreased radiation transmittance of the boundary layer. The unique vantage point provided by the space environment yields amounts and quality of data, along with full profile information to the top of the atmosphere that cannot be replicated with in-atmosphere instrumentation.

Key technological differences between non-space and space-based instruments reside in the lack of a cold-calibration target (space instruments can get their cold calibration via deep-space as a target) and the use of non-space-qualified componentry.

For the development of a space-based instrument like the Bureau's MSM-PF, some technological solutions and working principles can nonetheless be carried over from an airborne instrument to be evolved into a space instrument, paving the way for partnerships and collaboration. However, these two environments are radically different from each other. As such, an airborne instrument will require significant work to be adapted and qualified for space flight.

Very little information on this emerging class of digital/hyperspectral instruments was available at the time of writing this document. To date, no digital/hyperspectral space-based microwave sounders have been launched in space, thus presenting an opportunity for Australia to be a leader in this new class of instruments.

The following instruments have been identified and may be considered further in future work:

Airborne instruments

- HAMMR
- HiSRAMS
- HYMPI
- SAPHIR-NG

Space instruments (concepts)

- HYMAS (adaptation of the COSMIR scanhead).
- HYMS

An initial survey of these instruments' specifications has yielded insufficient information to be presented in a table. Importantly, instrument size, weight and power could not be determined. References for the HYMAS and HYMS instruments are included below; however, airborne instrument designs can still be researched and leveraged to benefit the development of the Bureau's MSM.

References – *All links are valid as of 14/02/2023*

HYMAS

- https://ntrs.nasa.gov/api/citations/20150002856/downloads/20150002856.pdf
- https://www.eoportal.org/other-space-activities/hymas

HYMS

- https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1002/2015JD023331
- https://spacenews.com/spire-adding-microwave-sounders-to-improve-weather-forecasts/
- https://ntrs.nasa.gov/api/citations/20120015408/downloads/20120015408.pdf

3.2.3 Mission benefits and industry growth opportunities

An Australian-developed operational Microwave Sounding Mission would make Australia a forefront player and contributor to the global meteorological observing system. As such, new partnerships and opportunities are likely to arise, both before and after the deployment of the capability. The mission's benefits include the following:

- Fostering the Australian space industry into transitioning to building and operating SmallSat class spacecraft.
- Upskilling the Australian workforce and gaining world-leading expertise in next-generation microwave sounding instrumentation.
- Increasing Australia's data sovereignty and security.
- Developing novel technologies and concepts through a hyperspectral microwave sounder.
- Providing the international weather community with new, high-quality, timely data, thus benefiting the global population through more reliable weather forecasting.
- Encouraging technology transfers with key partners such as the USA and Europe.

3.3 Pathways towards operational capability

Operational capability for the Bureau's MSM is envisaged as a constellation of identical small satellites in various orbits enabling high-quality data to be gathered with a high temporal resolution. Achieving this operational capability requires a measured-step approach to balance cost, schedule and technological risks. Several pathways leading to this capability were identified and are presented in the next sections.

3.3.1 SmallSat pathfinder

This is the option examined in this report. A notional MSM-PF would be designed to be as similar as possible to the final constellation satellites and would therefore be the best option to retire cost, schedule and technological risks for the MSM constellation. An MSM-PF would also increase the Australian space industry's capability in building small satellites, which can be leveraged later when the MSM constellation is developed.

3.3.2 CubeSat pathfinder

To reduce the pathfinder mission risk and significantly reduce cost, a limited-capability pathfinder could allow the Australian industry to develop parts of the payload instrumentation and test them in flight on a smaller platform.

For example, a digital spectrometer could be flown on a CubeSat with a smaller antenna and fewer frequencies. Whilst such a pathfinder would almost certainly not meet many of the mission requirements (for example, it would likely not be able to support 50-60GHz sensing due to antenna size limitations), it would be significantly less expensive in comparison with the development of a fully capable MSM-PF as envisaged in this report.

3.3.3 Existing SSMIS front-end adaptation

Another option proposed by the US Space Force could produce a very capable instrument via a shared development pathway. SSMIS is an operational mission that has flown on Defense Meteorological Satellite Program (DMSP) satellites between F-16 and F-19. SSMIS observations are already assimilated by Bureau models and are used by TC forecasters. An additional SSMIS instrument was due to be flown on DMSP-20 but was never launched. <u>The proposal would combine an Australian digital spectrometer back-end with the front-end from the remaining SSMIS unit in storage in the USA[*].</u>

One proposal for launch would be to modify the instrument as an International Space Station (ISS) mission (some instrument modifications would be required). The Space Force has hosted several instruments on the ISS (including COWVR, a microwave wind vector instrument) and would undertake negotiations to host this instrument. Although integration and testing would be undertaken in the USA, Australian engineers could be involved. There may also be hosting possibilities with Department of Defense SmallSat missions.

Both of these options deliver the following advantages:

- Significantly reduce the cost of a pathfinder mission
- Focus the Australian capability on building and demonstrating the digital spectrometer in LEO, significantly lowering the risk to the launch of the pathfinder

[*] The HyMAS team is currently achieving a similar task by repurposing the COSMIR front-end (precursor to SSMIS) and developing a digital back-end to fit.

The SSMIS pathway additionally provides the following:

- Re-use of high-quality flight-proven instrumentation
- Inclusion of a range of frequencies that may otherwise be out of reach of a pathfinder mission, providing a significant increase in surface and precipitation-sensing capability, also supporting soil moisture and cryosphere applications
- The chance to develop a meaningful partnership with organisations in the US with significant expertise in both microwave sounding and satellite instrument development, in particular, the University of Colorado and the United States Space Force
- Possible provision of complementary observations coincident with heavy maritime rain and ocean wind vectors from the microwave instrument COWVR which is currently housed on the ISS, thus increasing the value of the data from both instruments

3.3.4 Ground demonstrator

Another technology development pathway commonly used in payload development is building a ground-based instrument and/or airborne one before embarking on a space-based pathfinder. This option would allow the development of relevant instrumentation, including antennas and a digital spectrometer, at a vastly reduced cost and risk. Measurement campaigns could then provide observational data that can be used for scientific studies. The disadvantages of this route are:

- An upward-looking radiometer has a different sensitivity from a satellite radiometer's: most of the molecules in the atmosphere are near the surface, so signals from the top of the atmosphere are obscured. For satellites, the atmosphere has a high transmissivity above the boundary layer, thus allowing a near-complete vertical profile to be observed.
- This route does not provide opportunities for space-qualification of components.

It is worth noting that there could be a use-case for well-calibrated ground-based instrumentation to provide static lower-atmosphere profile information. The data from such an instrument could be used as a surface observation or for calibration and validation campaigns as a source of ground truth.

4 Mission Concept

This section proposes a mission concept developed by study participants during and after the study.

4.1 Spacecraft overview

The MSM-PF is a SmallSat class spacecraft flying a hyperspectral microwave sounder in LEO orbit. It would be the precursor to the MSM constellation that aims to provide high-quality atmospheric temperature and humidity data with low latency and excellent temporal resolution. Table 7 gives an overview of the proposed spacecraft's specifications.

Table 7: Overview of the proposed spacecraft specifications.

Specification	Value	Unit	Notes/Reference
Operational mission life	3	years	As per MSM-USR-15-T
Orbit	SSO 605.5 km 05:30 LTAN	-	Section 4.3.2, Table 9.
Dry mass	152.9	kg	Sections 6.4.1 and 6.4.2.
Wet mass	169.5	kg	
Size	~ 74 x 74 x 74	cm^3	Section 6.3.3.
Orbit average power	182.6	W	Section 6.2.1.
Yearly data volume	8	TB	Section 6.1.1, Table 20.
Downlink data rate	23.7	Mbps	Section 6.1.
Data storage capacity	> 10.9	GB	Section 6.1.1.
Pointing knowledge	0.09	deg	As per MSM-USR-08-O (10 km Ground Sampling Distance (GSD)).

4.2 Concept of operations

This section presents a high-level concept of operations of the MSM-PF. This concept of operations was developed during the study conjointly between the ANCDF team and the customer team. Its goal is to describe when and how the spacecraft performs certain tasks or behaves in specific scenarios. This, in turn, informs the mission design.

The operational MSM mission is envisaged as a constellation of identical or near-identical spacecraft to which the MSM-PF is as similar as possible. <u>This section focusses on describing the operations of the MSM-PF spacecraft.</u> Example constellation configurations are presented in section 4.4.

4.2.1 Acquisition mode

The MSM-PF is conceptualized as a globally sensing satellite. The payload is, therefore, constantly operating (100% duty cycle) in acquisition mode.

It is envisaged that the payload remains active even during downlinking; however, implications in terms of radiofrequency interference (RFI) and thermal aspects have not been fully considered in this study.

4.2.2 Science data downlink mode

Science data will be downlinked using commercially provided ground stations (ground station as a service). Ground stations are selected based on their location to maximise data timeliness.

It is envisaged that a direct broadcasting capability could be implemented in the operational MSM constellation to meet the global data timeliness requirement.

4.2.3 Telemetry, tracking and command downlink mode

Telemetry and tracking data will be downlinked using one or more commercially provided ground stations (ground station as a service). The ground station could be located in Australia or be one of the ones used for science data downlinking. Commands will be issued via the same ground station. The mission is likely to be incorporated into an existing mission operations centre.

4.2.4 Propulsion mode

Propulsion is envisaged onboard the MSM-PF to maintain its orbit (station-keeping) and perform evasive manoeuvres (as required). It is also expected that propulsion will be necessary to reach the final orbit after launch (station acquisition) as well as de-orbiting at the mission’s end of life.

4.2.5 Operational pointing configuration

The spacecraft is continually nadir pointing to allow constant operation of the payload. The communications antennas must be placed on the same face of the spacecraft as the payload or deployed from one of the adjacent faces.

It is envisaged that the antennas will either be wide-beam (as proposed in this report) or be electronically steered and will, therefore, not require attitude changing for downlink.

4.2.6 Data processing and dissemination

The MSM-PF is expected and recommended to downlink all of its raw sensor data for quality and consistency evaluation. Data will be processed and stored using commercial services.

4.3 Orbit selection

This section presents the proposed orbit and the methodology for its selection. The orbit selection, the concept of operations, and the payload description are at the core of any space mission conceptual design phase. The selected orbit drives all the subsystems' design, including the payload, communications, thermal, power and propulsion subsystems.

4.3.1 Derived orbit requirements

This section proposes a set of orbit requirements for the MSM-PF mission derived from the mission objectives, programmatic requirements and end-user requirements outlined in Section 2. Subsequently, this section outlines the constraints these derived requirements impose on selecting an orbit for the MSM-PF mission.

Table 8 summarises the derived orbit requirements. Where applicable, derived requirements address the 'objective'-level specifications.

Table 8: MSM-PF derived orbit requirements.

ID	Derived Orbit Requirement	Driving Requirements
CDF-R-ORB-01	The orbit shall facilitate vacation of the LEO-protected region within 25 years after the end of the nominal mission.	MSM-PRG-04, relating to the responsible use of space.
CDF-R-ORB-02	The orbit shall either: ▪ Provide redundant coverage in the early morning, mid-morning and afternoon orbital planes that comprise the core WIGOS LEO component, or ▪ Increase temporal sampling frequency and robustness of the WIGOS LEO component by occupying a different orbital plane. *Note: the WIGOS Vision 2040 identifies a plan for three additional LEO orbit planes but does not yet specify any details*[6].	MSM-OBJ-09
CDF-R-ORB-03	The orbit shall provide global coverage to the instrument. *Note: de-scoping the MSM-PF mission to threshold specifications would reduce this requirement to provide coverage of Australia and its surrounds.*	MSM-USR-04 MSM-OBJ-10 (only achievable with global coverage)
CDF-R-ORB-04	The orbit shall enable a single spacecraft to achieve a temporal sampling frequency of 12 hours. *Note: objective/breakthrough requirements for temporal sampling are only applicable to an operational MSM constellation.*	MSM-USR-14
CDF-R-ORB-05	The orbit shall provide the MS instrument with a swath width greater than 2200 km. *Note: de-scoping the MSM-PF mission to threshold specifications would reduce this requirement to a swath width greater than 1800 km.*	MSM-USR-05

CDF-R-ORB-01 considers international guidelines for the mitigation of space debris. In particular, the MWS-PF spacecraft must vacate the LEO-protected region within 25 years of the end of the nominal mission to comply with the Inter-Agency Space Debris Coordination Committee (IDAC) guidelines[8]. Both atmospheric drag and onboard propulsion can ensure the MWS-PF spacecraft is compliant with this requirement. The orbit altitude determines the magnitude of the atmospheric drag force and, consequently, the fuel mass required at the end of the nominal mission to ensure de-orbit.

Figure 2 illustrates the orbit lifetime estimate for a spacecraft in an equatorial, circular orbit over an altitude range of 100 km to 700 km. An additional lifetime scaling factor of 1.2 – 1.4 applies for 90° inclination orbits at altitudes between 500 km and 650 km[9]. Additionally, the orbit lifetime estimation assumes the spacecraft's ballistic coefficient is 200 cm^2/kg. Higher ballistic coefficients result in a shorter orbit lifetime.

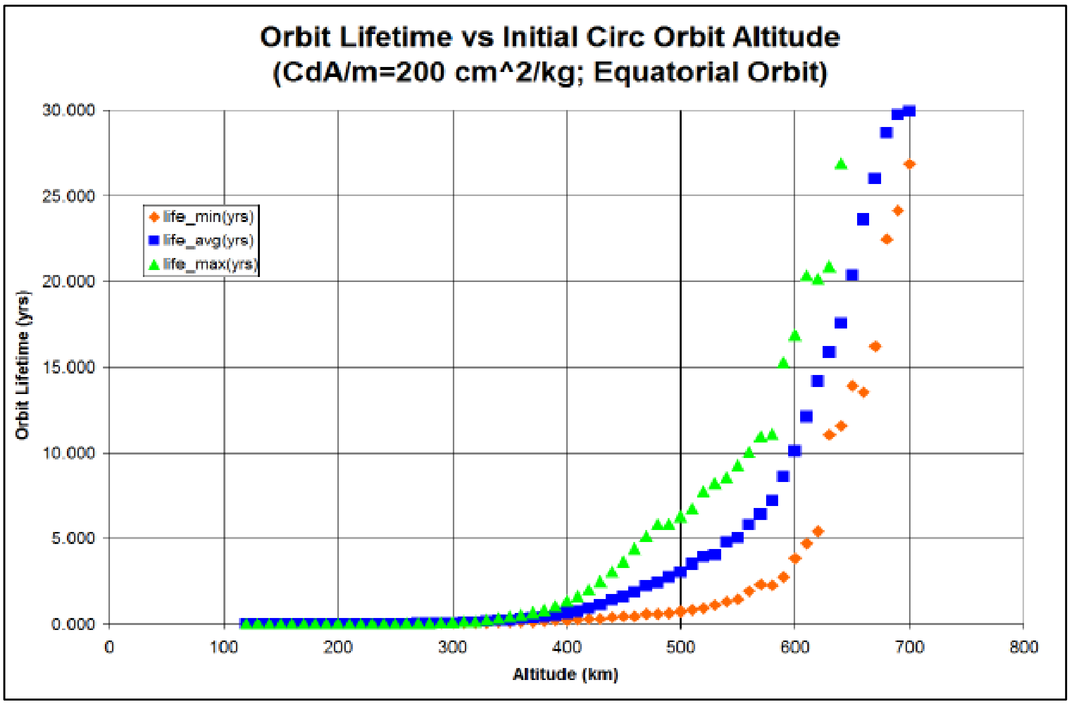

Figure 2: Relationship between orbit altitude and estimated orbit lifetime. [9]

The following observations from Figure 2 constrain the altitude of MSM-PF candidate orbits:

- Altitudes below 550 km guarantee de-orbit in less than 25 years. However, heightened atmospheric drag will necessitate more fuel for station keeping over the mission lifetime.
- Altitudes between 550 km and 625 km provide sufficient drag to de-orbit within 25 years and reduce the quantity of fuel required for station keeping.
- Altitudes above 625 km require fuel reserves to ensure de-orbit within 25 years. However, they require less fuel for station keeping.
- An orbit in which the spacecraft is ensured to decay within a reasonable time is desired to ensure this requirement is met even if the satellite is dead-on-arrival.

Therefore, candidate orbits must have an altitude between 550 km and 625 km.

CDF-R-ORB-02 frames the MSM-PF orbit selection in the wider context of the WIGOS. Presently, the WMO's vision for the 'backbone' LEO component of the WIGOS in 2040[6] comprises the following:

- A 'core' constellation of satellites in three Sun-synchronous orbital planes ('early morning', 'morning' and 'afternoon'), and
- Satellites in three additional Sun-synchronous orbit planes to improve robustness and time sampling.

Therefore, the MSM-PF orbit should be Sun-synchronous. There remains a choice regarding the specific orbit plane for the MSM-PF.

Sun Synchronous Orbits (SSOs) are polar orbits with orbital planes that precess at the same rate the Earth orbits the Sun. SSOs leverage the perturbing effects of the Earth's uneven gravitational field on the orbit plane to achieve this precession. Thus, SSOs maintain a constant angle with the Sun. They enable satellites to maintain the same local time along their ground track every orbit. For a given altitude, there is a specific inclination that yields the correct planar precession rate[*]. Therefore, station keeping is required to maintain the correct altitude throughout the mission lifetime.

SSOs are frequently discussed in terms of their Local Time of the Ascending Node (LTAN), which describes the local time when the spacecraft transits the equator travelling North. The local time at the descending node, when the spacecraft crosses the equator travelling South, is exactly 12 hours offset from the LTAN. The 'core' constellation in the WIGOS vision for 2040 therefore comprises:

- An 'early morning' orbit plane: 05:30 LTAN (equivalently, 17:30 LTAN)
- A 'morning' orbit plane: 09:30 LTAN (equivalently, 21:30 LTAN)
- An 'afternoon' orbit plane: 13:30 LTAN (equivalently, 01:30 LTAN)

The three additional SSO planes are not yet defined; however, time sampling is optimised if these orbit planes fit directly in-between the existing planes. Therefore, this report assumes the three additional planes are:

- 07:30 LTAN (equivalently, 19:30 LTAN)
- 11:30 LTAN (equivalently, 23:30 LTAN)
- 15:30 LTAN (equivalently, 03:30 LTAN)

CDF-R-ORB-03 is achievable at the objective-level specification using an SSO. SSOs are polar orbits and, consequently, cover all latitudes. A mid-inclination orbit, which does not cover high latitudes, can only meet the threshold requirement to provide coverage of Australia and a sea margin to cover coastal activity.

CDF-R-ORB-05 requires a swath width of 2200 km to meet objective-level requirements. Higher altitudes yield greater swath width at the expense of spatial resolution and SNR. Figure 3 below visualises the MSM-PF instrument's swath over the altitude range prescribed by CDF-R-MS-01. The calculation of swath width assumes an instrument with a 55° half-cone field-of-view as prescribed by MSM-USR-09 in Table 4. No suitable altitude can provide a swath width that meets the 2200 km requirement with the MSM-PF instrument. Orbits with altitudes greater than approximately 630 km can meet the breakthrough requirement of 2050 km; however, the platform will require more fuel mass for end-of-life de-orbit and may not de-orbit within 25 years if it is dead-on-arrival. Orbits with an altitude greater than 565 km meet the threshold requirement of an 1800 km swath width.

[*] For the altitude range considered for the MSM-PF mission, the inclination of SSOs is between 96° and 98°.

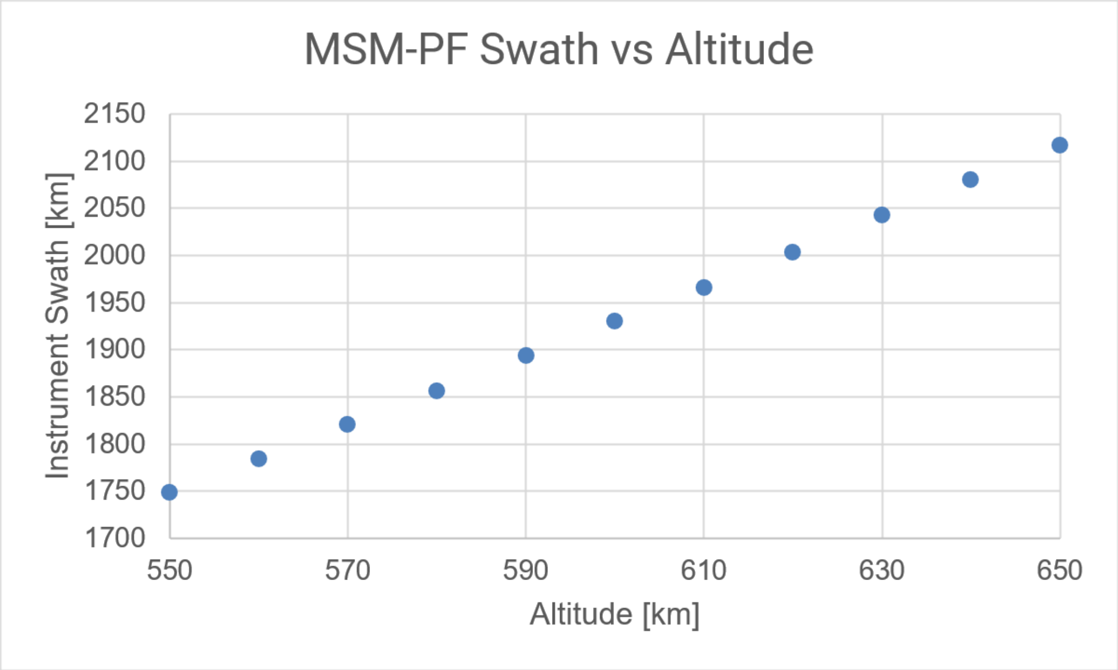

Figure 3: Relationship between orbit altitude and MSM-PF swath width.

The swath width does not increase appreciably between 600 km and 650 km altitudes. However, higher altitudes increase the NEΔT (therefore degrade the signal-to-noise ratio) and ground sampling distance (coarser spatial sampling) and increase the required end-of-life fuel mass. Therefore, altitudes close to 600 km offer a suitable trade-off between sensor area coverage rate, NEΔT, ground resolution and required fuel mass.

4.3.2 Primary orbit candidate: early morning Sun-synchronous orbit

This section outlines the selection of a single candidate orbit that satisfactorily meets the derived orbit requirements presented in section 4.3.1. The selected orbit is used throughout the mission design developed in this report. However, many orbits could equivalently meet these requirements, and the orbit selection presented in this section is not prescriptive.

The discussion of the derived requirements indicates that a suitable orbit for the MSM-PF mission should:

- Be Sun-synchronous with an LTAN compatible with the WIGOS vision for 2040,
- Occupy an altitude between 550 km and 650 km,
- Provide global coverage (to meet objective-level requirements), and
- Maximise swath width, noting the trade-off with increasing the required end-of-life fuel mass at altitudes above 600 km.

The WIGOS vision for 2040 has not specified the details of the anticipated additional SSO planes that will complement the 'core' constellation at the time of writing. Therefore, the MSM-PF can best contribute to the GOS by occupying an LTAN presently utilised by operational meteorological missions to improve system redundancy. Presently, there is an inadequate density of international observations from early morning SSOs[10]. Therefore, an LTAN of 05:30 is chosen for the candidate orbit.

Careful selection of the SSO parameters can ensure the MSM-PF follows a ground track that repeats after a prescribed number of days. A so-called 'repeat SSO' provides spatial consistency, as the MSM-PF-Earth geometry repeats after one 'recurrence period' concludes. Figure 4 outlines various repeat SSOs available for the MSM-PF. All points in the figure below provide complete global coverage with the MSM instrument. A 7-day repeat SSO is achievable at an altitude of 605.52 km with a swath width of 1949.43 km.

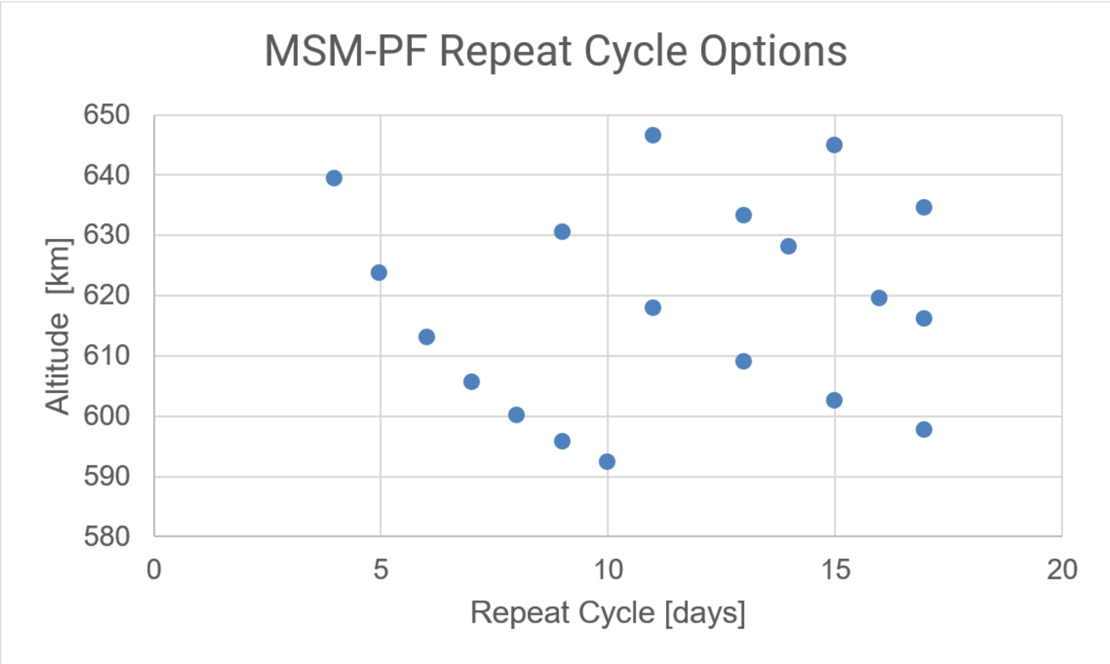

Figure 4: Altitudes of repeat SSOs with a repeat cycle of 20 days or less.

This report uses a 05:30 LTAN recurrent SSO with a 7-day repeat cycle as a baseline for the MSM-PF orbit. The ground track repeats after the spacecraft has completed 104 orbits of the Earth in just over 7 days. Table 9 shows the parameters of the selected candidate orbit.

Table 9: Parameters of primary candidate MSM-PF orbit, 05:30 LTAN SSO.

ID	Orbit Parameter	Value	Unit
CDF-S-ORB-01	Altitude	605.52	km
CDF-S-ORB-02	Inclination	97.83	deg
CDF-S-ORB-03	Period	96.92	min
CDF-S-ORB-04	Repeat Cycle	7	days
CDF-S-ORB-05	Recurrence Grid Interval	385.34	km
CDF-S-ORB-06	LTAN	05:30	-

The wide swath of the MSM-PF instrument results in a high area coverage rate. Figure 5 visualises the sensor's area coverage after 4 orbits (approximately 6 hours). For comparison to an existing state-of-the-art microwave sounder, Figure 6 shows the area coverage of the ATMS instrument hosted on NOAA-20 after 6 hours. The ATMS instrument's swath width is larger than MSM-PF, predominantly thanks to NOAA-20's higher orbit altitude, approximately 833 km[11].

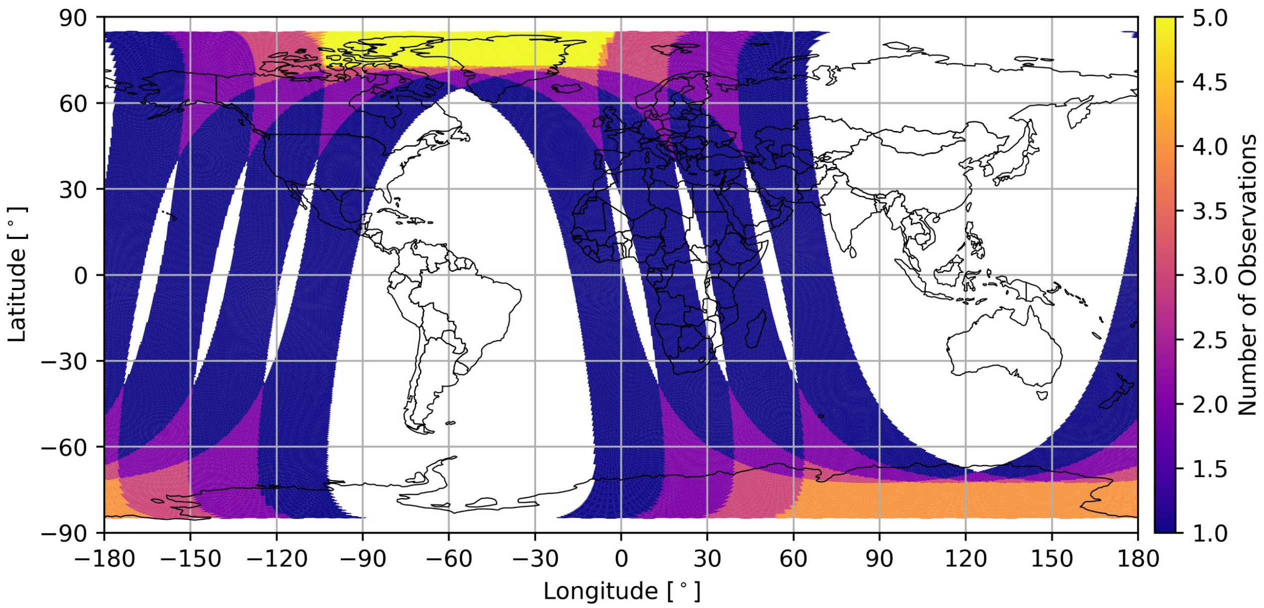

Figure 5: MSM-PF sensor coverage in 05:30 LTAN SSO after 4 orbits [6.47 hours].

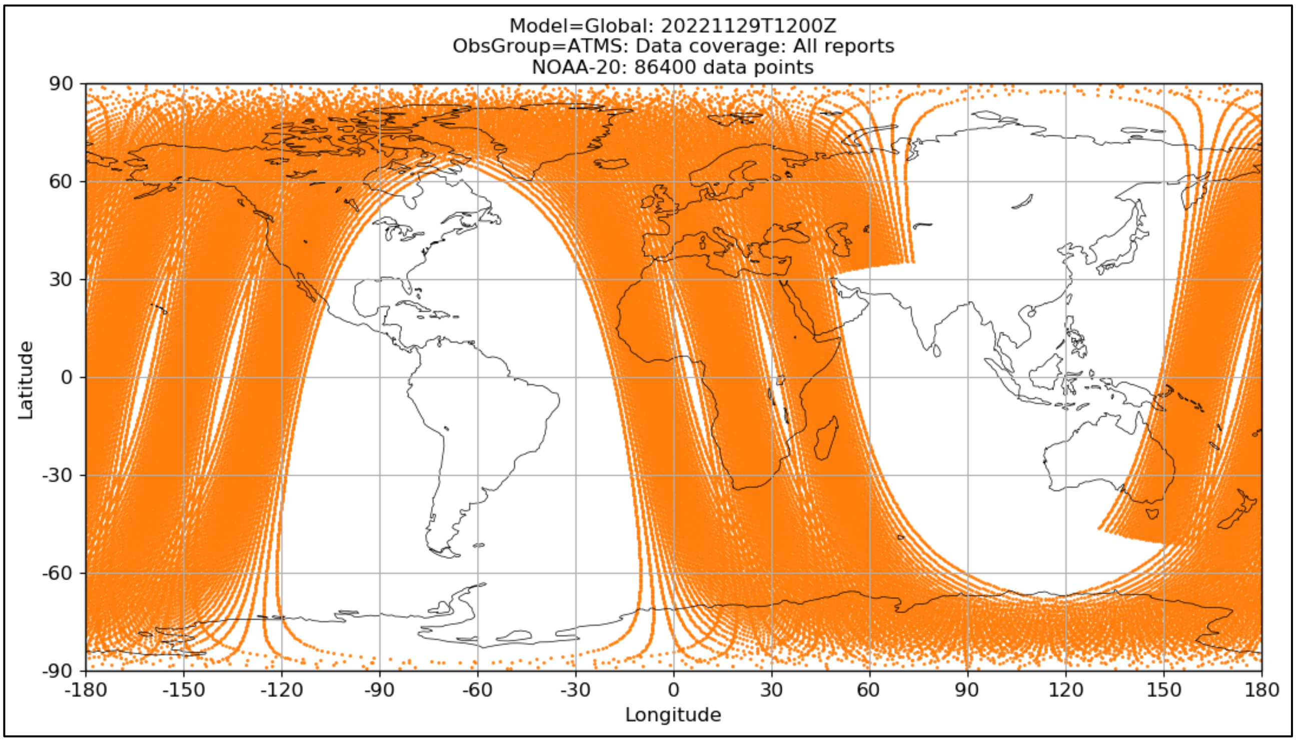

Figure 6: 6-hour coverage from the ATMS instrument on NOAA-20 in 13:25 LTAN SSO (source: Bureau of Meteorology).

Figure 7 and Figure 8 below visualise the MSM-PF sensor's area coverage after 15 orbits (approximately corresponding to one day) and 104 orbits (approximately corresponding to 7 days), respectively. After one day, the MSM-PF instrument has almost achieved complete global coverage thanks to its wide swath width. After 7 days, the instrument has achieved complete global coverage, and the ground track will repeat. During this period, the MSM-PF observes locations in Australia between 10 and 20 times (1-3 observations per day on average). The MSM-PF makes the most observations at the poles as it passes these regions every orbit.

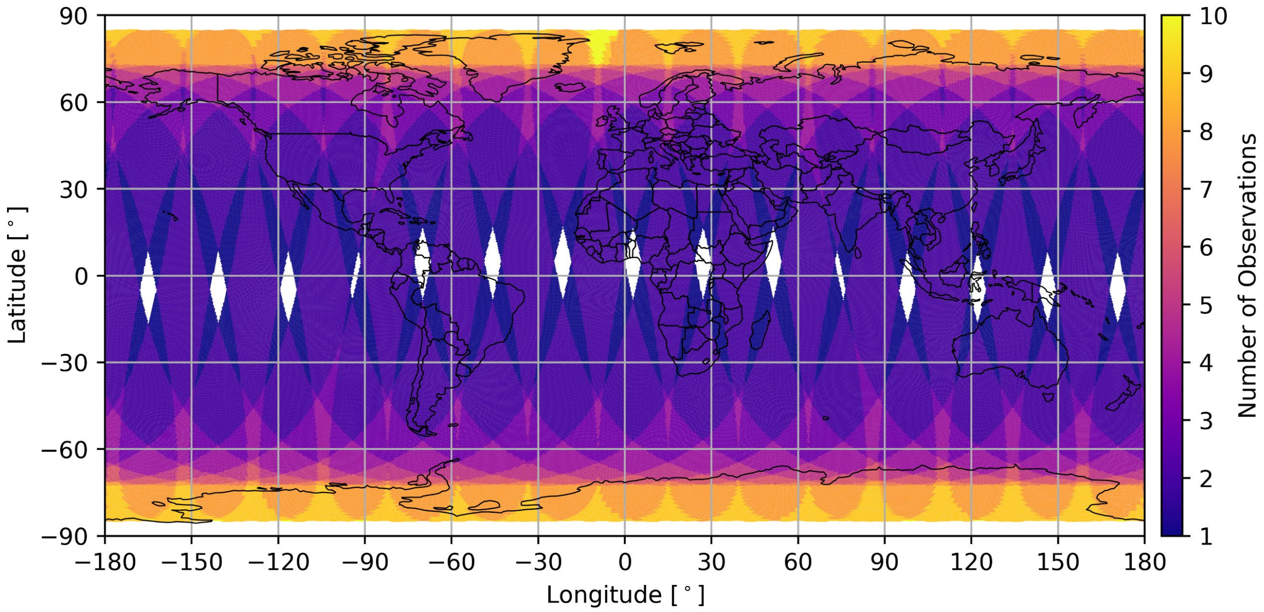

Figure 7: MSM-PF sensor coverage in 05:30 LTAN SSO after 15 orbits [1.01 days].

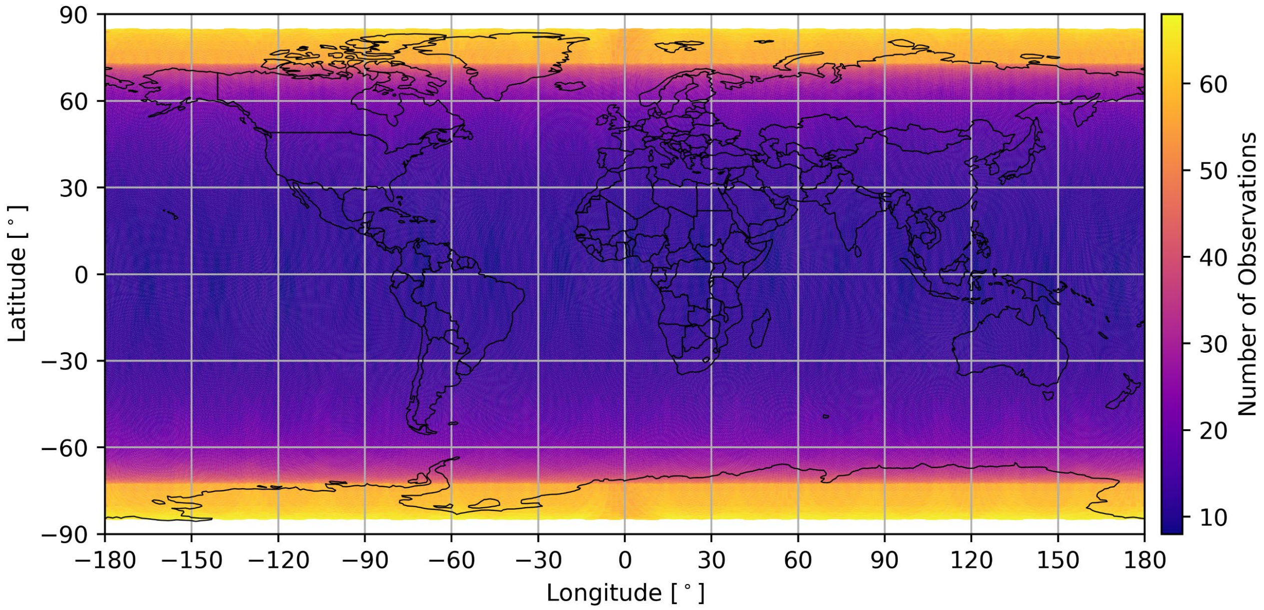

Figure 8: MSM-PF sensor coverage in 05:30 LTAN SSO after a full repeat cycle of 104 orbits [7.01 days].

Figure 9 below displays the mean time interval between MSM-PF observations of a given location for one 7-day repeat cycle. The longest mean sampling intervals, roughly 18 hours, occur in narrow bands near the equator including Northern Australia. The mean sampling interval over Australia is 13.9 hours, and the minimum is 11.2 hours. The mean sampling interval is lowest over the poles, approximately 2.3 hours, as the spacecraft transits the poles every orbit. Therefore, the 05:30 LTAN candidate orbit proposed in this Section does not meet the time sampling requirement, CDF-R-ORB-04, for many locations on Earth. If the sampling interval over Australia is prioritised over global coverage, this would be better achieved with a mid- or low-inclination orbit (see next section).

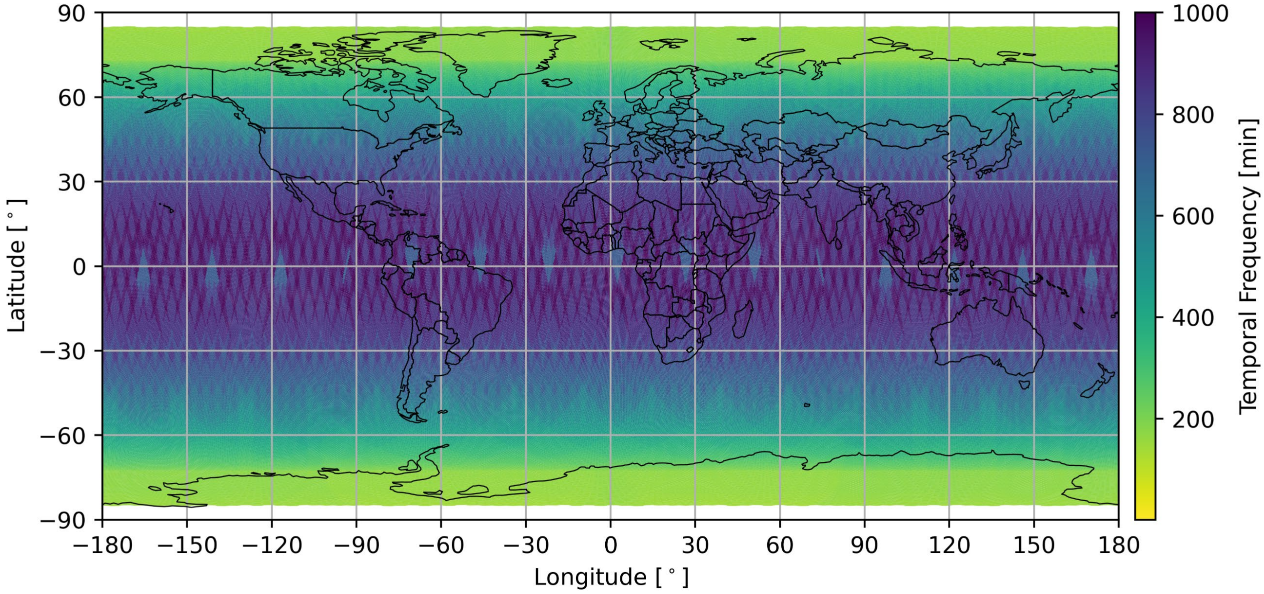

Figure 9: Mean time interval between samples for MSM-PF in 05:30 LTAN SSO.

4.3.3 Discussion of alternative orbits

Mid-inclination LEOs can meet the major mission requirements for tropical cyclone monitoring and regional Australian NWP. To ensure the ground track covers all of Australia, the minimum inclination for a LEO orbit is approximately 43°. Compared with SSOs like the candidate orbit proposed in section 4.3.2, mid-inclination LEOs offer some advantages:

- Mid-inclination LEOs provide more frequent observations of locations in the mid-latitudes. As there are several polar orbiting satellites carrying microwave sounders, the mid-inclination orbit is still very desirable to global NWP centres as it provides a complementary measurement platform. For example, the SAPHIR instrument on the Megha-Tropiques satellite was very successful in global NWP applications[12].
- Mid-inclination LEOs require less energy to enter, so launchers can carry more mass to orbit. Therefore, mid-inclination launches are typically cheaper per unit of mass as the cost divides among more customers.
- Mid-inclination LEOs do not require a precise altitude/inclination pairing; this allows the MSM-PF to pursue more rideshare opportunities, decreasing the schedule risk and potential launch cost.
- Mid-inclination LEOs do not require extensive station keeping, as they don't need to maintain precise orbit elements.

However, the fundamental geometry of mid-inclination LEOs trades the above advantages with the following drawbacks:

- Mid-inclination LEOs cannot provide global coverage, reducing their usefulness for global NWP and the Bureau's Antarctic applications.
- Mid-inclination LEOs cannot provide redundant or additional capacity to the SSO planes identified in the WIGOS 2040 vision.
- Observations will not have consistent local solar time.

The M2 mission, presently operated by UNSW Canberra Space, launched into a 550 km, 45° LEO on a Rocket Lab Electron launch vehicle in 2021. The M2 orbit is a typical ride-share orbit and could be considered for MSM-PF. The M2 orbit parameters are outlined in Table 10 below. The altitude of this orbit yields a swath width of 1750 km, which is slightly lower than the threshold requirement. However, the analysis presented using this orbit is intended to demonstrate some of the trade-offs the Bureau may consider when pursuing a cheaper, more flexible mid-inclination LEO over an SSO.

Table 10: UNSW Canberra Space M2 orbit parameters.

Orbit Parameter	Value	Unit
Altitude	550	km
Inclination	45	deg
Period	95.65	min

Figure 10, Figure 11 and Figure 12 below visualise the MSM-PF sensor's coverage in a mid-inclined orbit after approximately 6 hours, 1 day and 7 days, respectively. The sensor's coverage extends significantly beyond 45° latitude due to the sensor's large swath width. After 1 day, the MSM-PF provides nearly complete coverage between +/-53° latitude. After 7 days, the coverage heatmap shows the most observations are concentrated over a narrow belt at approximately +/-38° latitude. On average, there are approximately 15-20 observations over locations in Australia during the 7-day period. A comparison of Figure 8 and Figure 12 demonstrates that the 45° LEO yields a slightly higher density of observations over Australia than the 05:30 LTAN SSO.

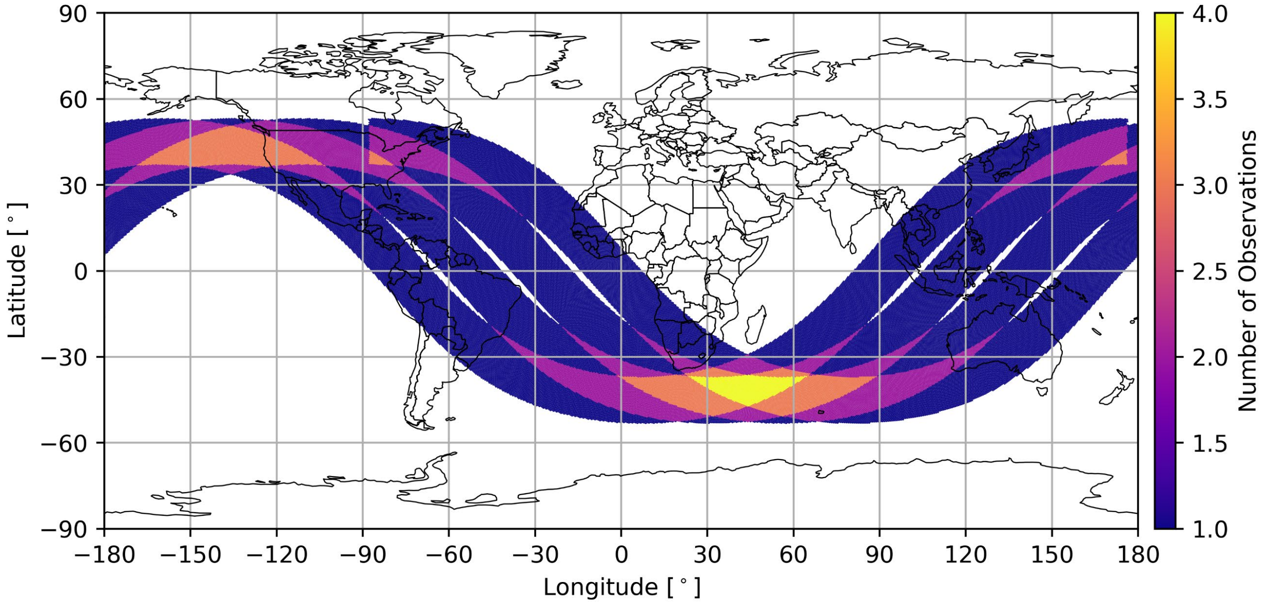

Figure 10: MSM-PF sensor coverage in 45° orbit after 4 orbits [6.38 hours].

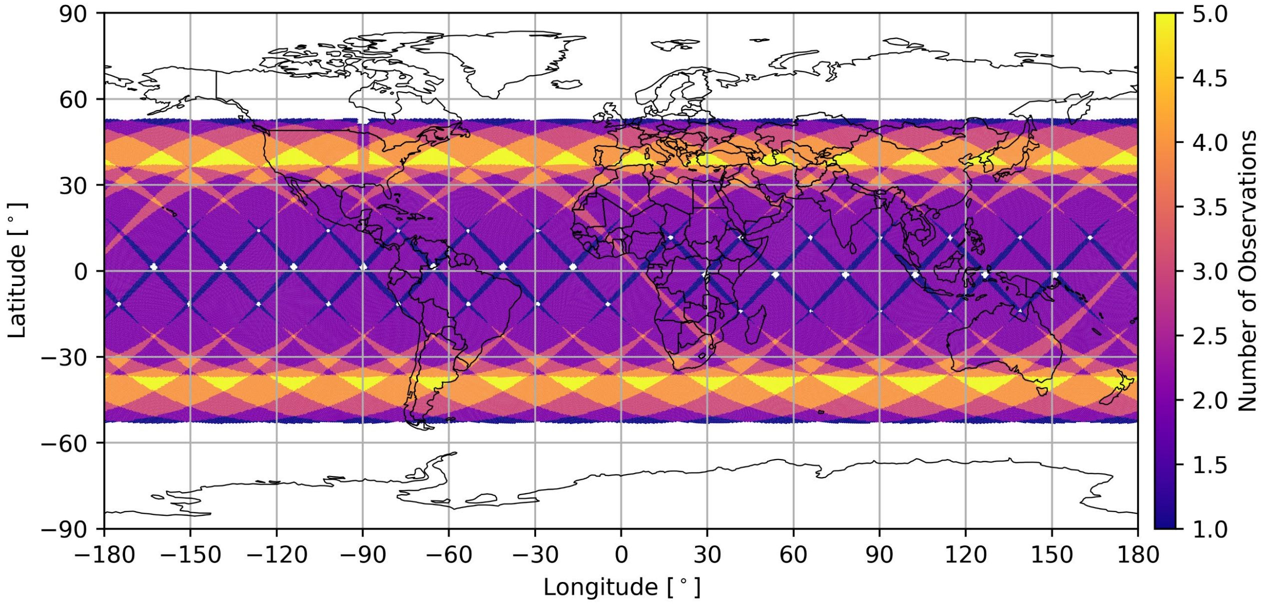

Figure 11: MSM-PF sensor coverage in 45° orbit after 15 orbits [1.00 days].

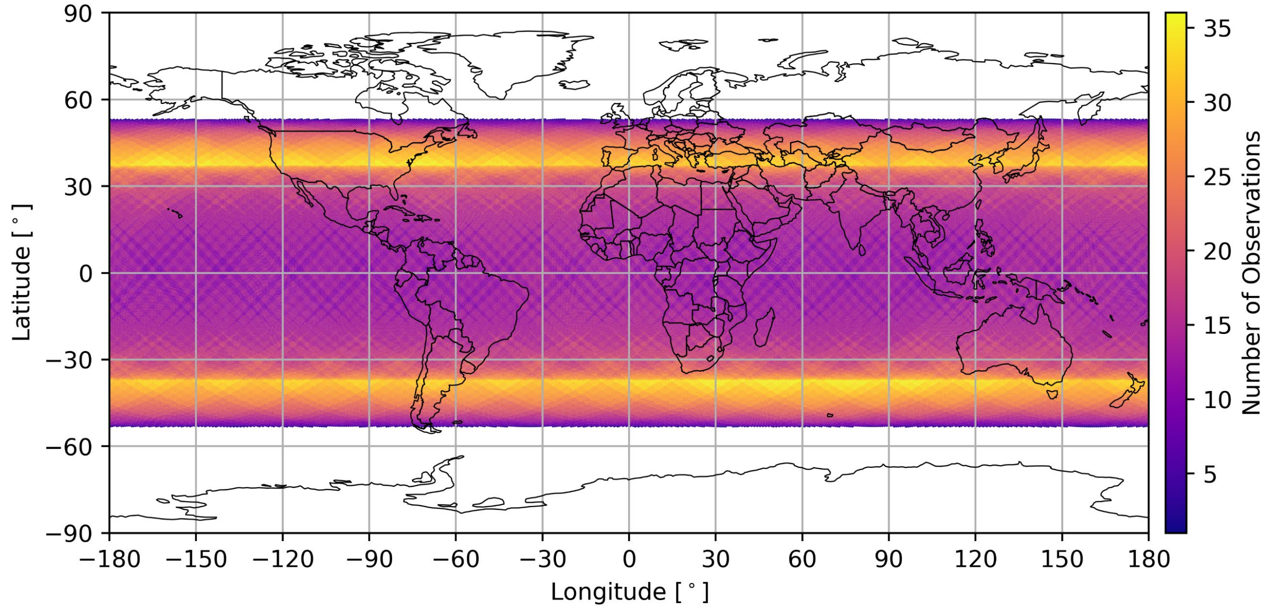

Figure 12: MSM-PF sensor coverage in 45° orbit after 106 orbits [7.04 days].

Figure 13 below visualises the mean time interval between observations from the 45° orbit over the simulated 7-day period. The shortest sampling period, approximately 4.5 hours, occurs at approximately +/-38° latitude. Over Australia, the mean sampling interval is approximately 10.2 hours, comparable to the 05:30 LTAN SSO presented in Section 4.3.2. The maximum sampling interval over Australia is 16.4 hours and occurs near the equator.

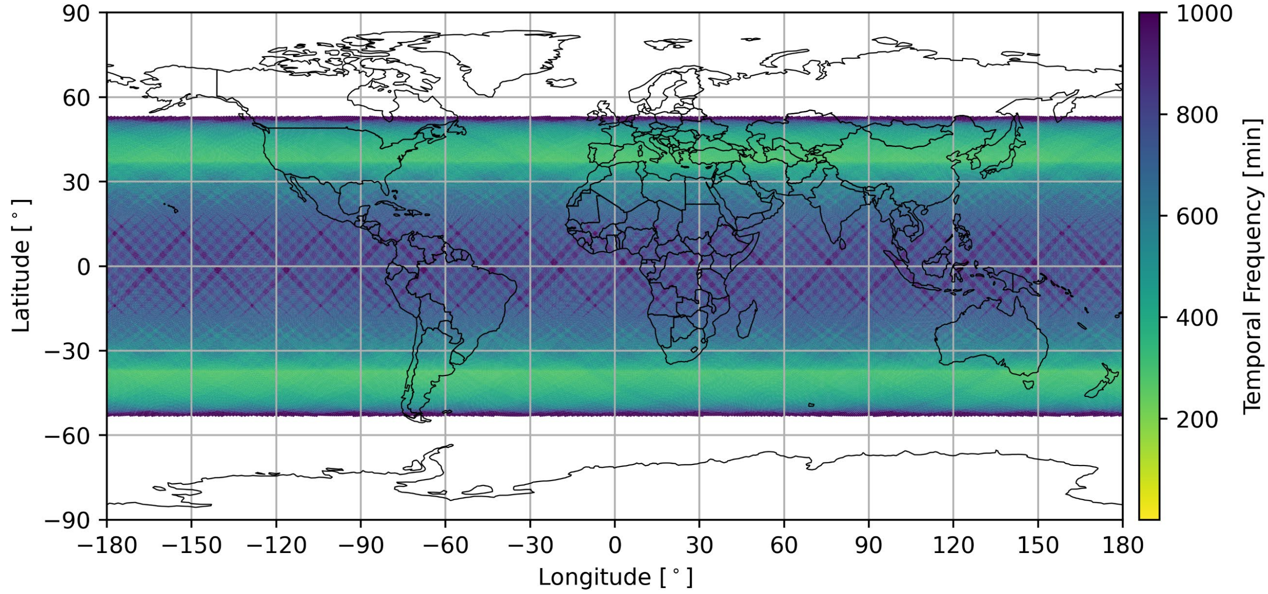

Figure 13: Mean time interval between samples for MSM-PF in 45° orbit.

4.4 MSM constellation considerations

This section analyses the temporal resolution performance attainable from a constellation of operational MSM spacecraft as envisaged after the MSM-PF mission. Constellations comprise multiple spacecraft that can occupy the same orbit plane, multiple orbit planes of the same orbit type, and even multiple orbit planes spanning different altitudes and inclinations.

A prescriptive MSM constellation design that optimises cost and temporal resolution is the scope of future work. The analysis presented in this report uses a small set of example constellation configurations to explore the trade space and form the basis of future studies. The configurations explored in this section assume that the MSM-PF spacecraft in a 05:30 LTAN orbit is still functional. In addition to this spacecraft, the constellation scenarios introduce additional spacecraft with the same payload as the MSM-PF, in either additional SSO orbit planes or 45° orbits with offset Right Ascension of the Ascending Node (RAAN)*. The constellation examples.

Table 11: Example MSM constellation configurations.

Name	Base Spacecraft	SSO Slots	Mid-Inclination Slots
Example 1	MSM-PF, 05:30 LTAN SSO	3 x SSO (07:30, 11:30, 15:30 LTANs)	0
Example 2	MSM-PF, 05:30 LTAN SSO	0	3 x 45°, 120° RAAN offset
Example 3	MSM-PF, 05:30 LTAN SSO	3 x SSO (07:30, 11:30, 15:30 LTANs)	3 x 45°, 120° RAAN offset

Note that the orbit requirements may change between the MSM-PF mission and a follow-up constellation. In particular, transitioning to an operational constellation could shift the orbit altitude constraints to optimise coverage, allowing for altitudes above 700 km that yield wider swath width (commensurate with ATMS on NOAA-20, for example). This would further improve the temporal resolution performance of the MSM constellation.

4.4.1 Constellation example 1

The first constellation configuration example comprises the initial MSM-PF spacecraft in a 05:30 LTAN orbit at 605.52 km altitude, complemented by 3 additional spacecraft in additional SSO planes. These planes are the 07:30, 11:30 and 15:30 LTAN slots thought to be the additional SSO planes in the WIGOS 2040 vision.

Figure 14 visualises the mean temporal sampling interval attained by the constellation after simulating the full 7-day repeat cycle. The longest duration between observations anywhere on the globe is approximately 4.6 hours. Over the Australian region, the temporal resolution is between 2.9 hours and 3.9 hours. Therefore, this constellation configuration is close to meeting the breakthrough temporal sampling frequency of less than 3 hours globally. However, the constellation only meets the objective requirement of sub-hourly over the poles. The best temporal resolution, approximately 36 minutes, is achieved at the poles.

* The RAAN of an orbit defines the orientation of its plane relative to other orbits; for example, two otherwise identical 45° orbits with RAANs of 0° and 180°, respectively, would be perpendicular to one another.

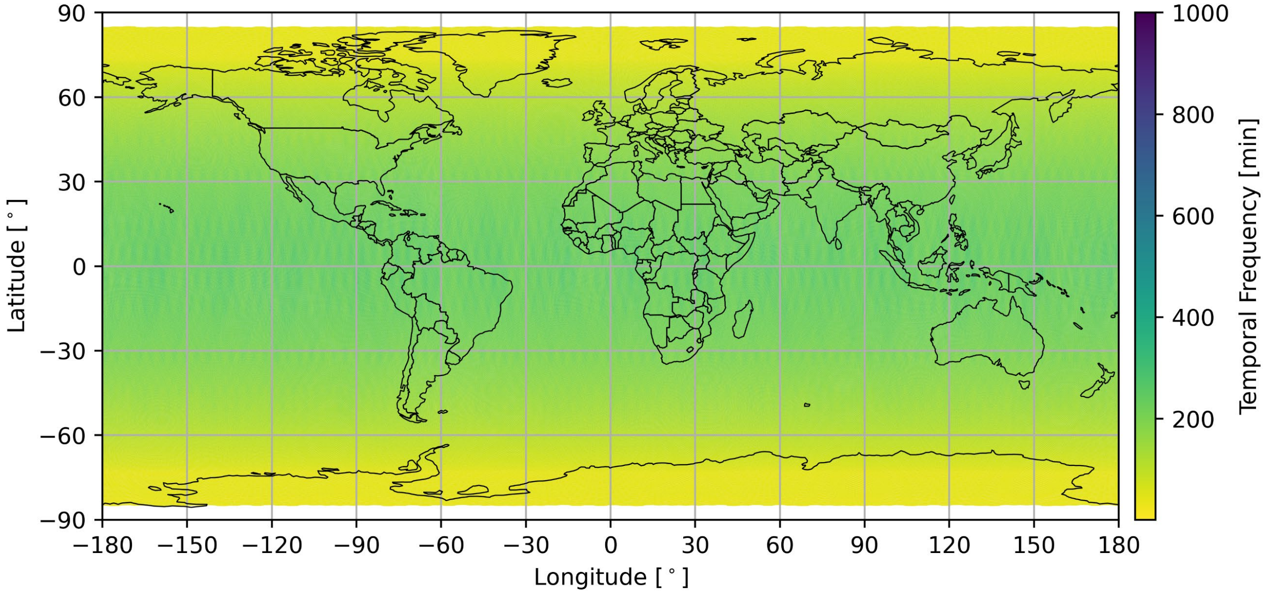

Figure 14: Mean time interval between samples for MSM constellation example 1.

4.4.2 Constellation example 2

The second constellation example comprises the initial MSM-PF spacecraft in a 05:30 LTAN orbit at 605.52 km altitude, complemented by 3 additional spacecraft in 550 km, 45° orbit planes. Each 45° orbit plane is spaced with a RAAN separation of 120° to maximise their effect on temporal resolution.

Figure 15 visualises the temporal resolution obtained from this constellation configuration over the full 7-day repeat cycle of the 05:30 LTAN SSO. High latitude regions, between approximately +/-53° and +/-75°, experience low temporal resolution with a global minimum of 10.5 hours. This frequency does not meet the threshold global temporal sampling requirement for a constellation. The best temporal frequencies are attained between +/-38° and +/-52°. The best temporal resolution is approximately 1.4 hours near +/-38°, increasing to approximately 2.9 hours at +/-52°. Over the rest of the Australian region, the temporal resolution does not exceed approximately 3.3 hours. Therefore, over regions of interest, this constellation, at best, meets the breakthrough temporal resolution requirement and, at worst, falls short by 30 minutes.

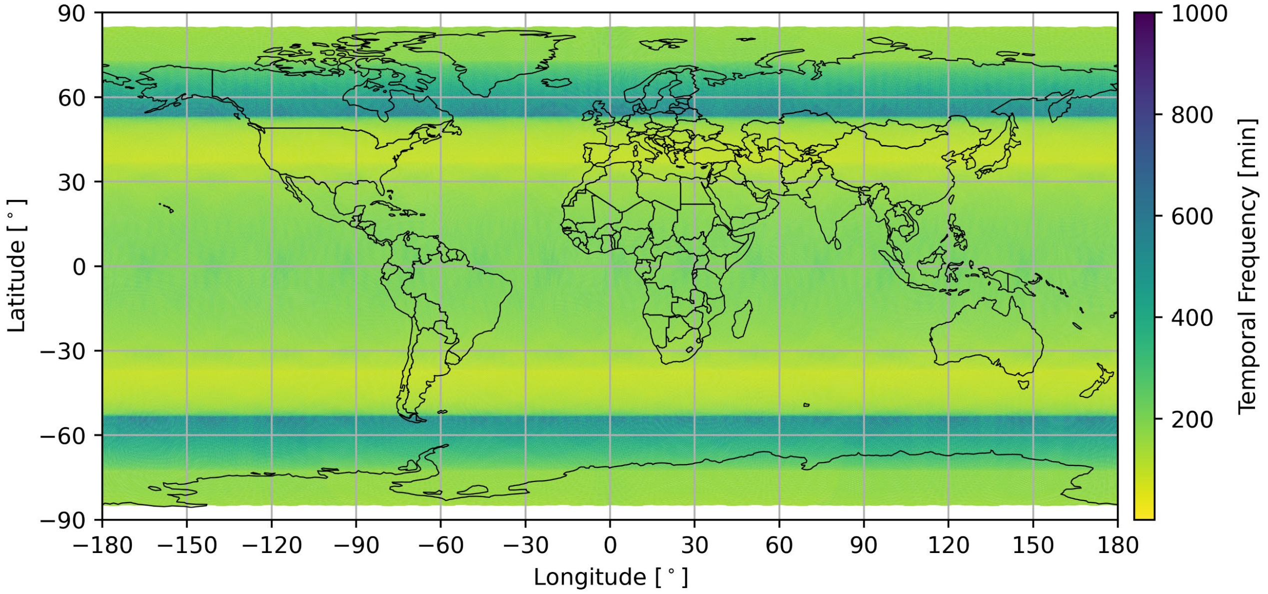

Figure 15: Mean time interval between samples for MSM constellation example 2.

4.4.3 Constellation example 3

The third constellation example combines those presented in sections 4.4.1 and 4.4.2. It comprises the base MSM-PF spacecraft in a 05:30 LTAN orbit at 605.52 km, three spacecraft in identical SSOs at 07:30, 11:30 and 15:30 LTANs, along with three 550 km, 45° orbits with RAANs offset by 120°.

The best temporal resolution, approximately 36 minutes, is attained at the poles. Additionally, temporal frequencies between approximately 1.1 and 1.5 hours are attained within two latitude bands, between +/-52° and +/-38°. These regions meet the breakthrough temporal resolution requirement of less than 3 hours. Over most of the Australian region, the sampling frequency is between approximately 1.1 and 2 hours. Therefore, this constellation configuration can meet the breakthrough requirement over the major regions of interest.

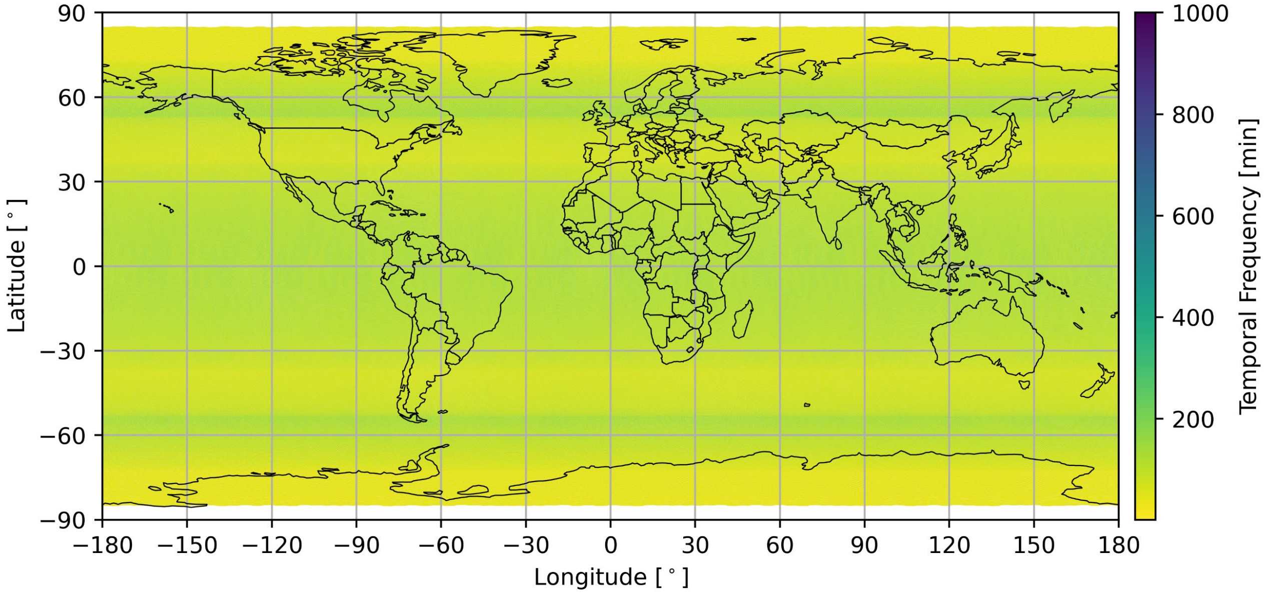

Figure 16: Mean time interval between samples for MSM constellation example 3.

5 Preliminary Payload Design

5.1 Purpose and scope of this section

In this section, a payload architecture and concept are proposed and explored. At this stage, this report does not make any final recommendation on the design of this instrument. A significant amount of work associated with an extensive capability and technology survey is required before fully engaging in any particular instrument design pathway, a work that is outside the scope of this Pre-Phase A study.

In all the spacecraft design work presented in subsequent sections, the most conservative assumptions in terms of payload size, weight, power and data generation were adopted in a way that whatever design path is chosen in future work, it is likely that the spacecraft architecture and specifications proposed in this document will be able to support it. Future work will further refine the concepts presented in this section.

5.2 Preliminary trade-offs

There are two major subsystems to a microwave sounder instrument, often referred to as the "front-end", which comprises the antenna and feed horns that collect the atmospheric radiation, and the "back-end", which comprises the spectrometer that receives the radiation via detectors and splits the radiation into different frequencies to form the measurements.

Front-ends typically fall into two categories: conical scanners and cross-track scanners. Back-ends also fall into two categories: analogue and digital back-ends, with only the latter allowing hyperspectral sensing.

The instrument's front-end and back-end are decoupled and can be adapted to each other.

The survey of the current art presented in section 3.2.2 shows that all currently flying instruments are analogue cross-track scanners (with the notable exception of SSMIS, an analogue conical scanner). Table 12 shows a classification of the surveyed instruments.

Table 12: Surveyed instruments classification.

	Analogue back-end	**Digital back-end –** *never flown*
Conical scanner front-end	SSMIS	HYMAS HYMS
Cross-track scanner front-end	ATMS, AWS, BOWIE-M, EON-MW, MWS	**MSM-PF** *(proposed)*

This study proposes to design the MSM-PF instrument as a cross-track scanner front-end with a digital spectrometer back-end. The following subsections justify this proposal.

5.2.1 Instrument back-end: Analogue VS digital spectrometer

The mission proposal is for a "hyperspectral" sounder, measuring around 1000-1800 channels (versus 10-20 for all existing instruments, see survey), spread mainly between 50-60 GHz and around 183 GHz. To deliver this capability, a digital spectrometer is required to split the incoming radiation into a large number (1000-1800) of spectral components.

There are two main potential benefits of a hyperspectral microwave sounder. Firstly, the increased spectral resolution would enable the instrument to measure the temperature and humidity profiles with a higher vertical resolution, as each channel will peak at a slightly different height in the atmosphere. The potential impact of a high vertical resolution has been explored in several papers[13,14,15,16,17,18]. The channels which give the largest benefit to NWP are ATMS 6 and 7 and AMSU-A 5, 6 and 7. These channels sense in the free troposphere. The ability to increase the number of channels spanning this frequency range would greatly benefit NWP and TC forecasting because of the likelihood of improved warm core anomaly analysis.

The second benefit of a hyperspectral microwave sounder is the possibility of mitigating Radio Frequency Interference (RFI). RFI is an increasing problem for passive microwave instrumentation, with telecommunications companies desiring more and more spectrum to enhance their services. Current RFI for passive channels is mostly at the lower frequency ranges (L-band, 2.4 GHz, in particular) and tends to strongly impact the observation. If RFI increases to impinge upon the main sounding frequencies as expected (e.g. the 89-90 GHz region being mooted for 6G), it will be important to design the instrument to minimise these effects.

For strong and narrow bandwidth RFI, a hyperspectral instrument could eliminate affected channels while retaining most of the information content. For broadband low-power RFI (as proposed for 6G[19]), it is worth investigating whether such a signal could be detected and removed using mathematical processing of the large number of channels sensed, such as principal component analysis. If this were possible, it could lead to enhanced machine learning options to mitigate low-level RFI.

In terms of instrument design, a digital back-end will trade an analogue spectrometer's relatively low power consumption for significant mass and volume savings (through the use of on-board processing). Therefore, the MSM-PF instrument is expected to be smaller and lighter than a comparably performing analogue instrument, albeit with a higher power consumption. However, in this study and given the conceptual stage of the payload’s development, conservative assumptions were made for all specifications and are exposed in section 5.5. In particular, the mass and volume estimates were based on existing analogue instruments.

It is worth noting that a major challenge of developing a hyperspectral microwave sounder resides in meeting data quality requirements in terms of temperature noise equivalent[20] (NEΔT). It is, however, expected that technological developments and the instruments currently being developed (such as the digital instruments identified in section 3.2.2.3) will ultimately allow digital hyperspectral instruments to meet or exceed current analogue instrument data quality levels[21] while providing unprecedented amounts of new data.

5.2.2 Instrument front-end: Cross-track scanner VS conical scanner

Two main types of instrument front-ends exist: conical and cross-track scanners. Conical scanners sample the instrument swath along a cone-shaped area. This type of front-end provides a constant spatial resolution, as opposed to the variable resolution provided by cross-track scanners.

With a relatively simpler design, cross-track scanners linearly scan the instrument swath across the satellite's ground track. This type of front-end benefits from significant heritage from previous instruments.

Figure 17 and Figure 18 illustrate how these two types of front-ends operate.

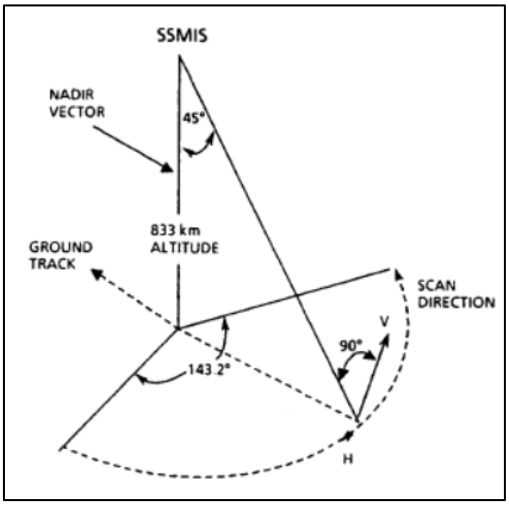

Figure 17: Example of a conical scanner – SSMIS (source: University of Colorado).

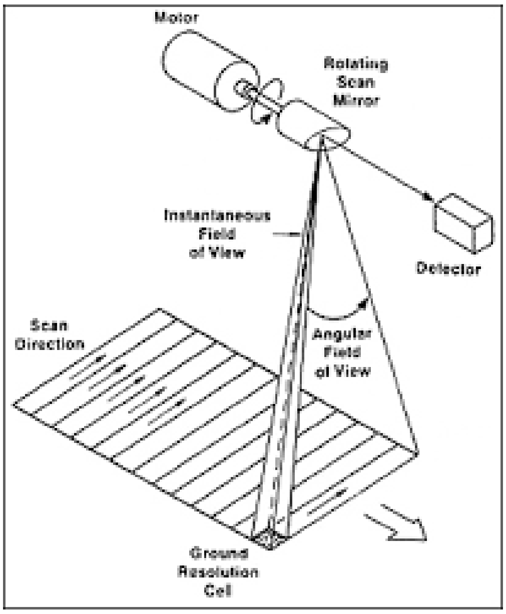

Figure 18: Example of a cross-track scanner (source: Canadian Centre for Remote Sensing).

Table 13 presents a high-level comparison drawn by participating payload experts during the study.

Table 13: Comparison of cross-track and conical scanners.

	Cross-track scanner	Conical scanner
Pros	▪ Relatively simpler design and significant technological heritage (see survey) ▪ More reliable calibration than a conical scanner	▪ Constant spatial resolution ▪ Multiple views of the same ground footprint ▪ Requires less volume than a cross-track scanner ▪ Provides coincident data between channels
Cons	▪ Variable spatial resolution (best at nadir but coarser everywhere else)	▪ More complex design than a cross-track scanner

<u>Either type of instrument would meet the mission requirements of MSM-PF. For its relative simplicity, a cross-track scanner front-end is recommended and proposed in this report, leaving the technology research and development efforts focused on the much more novel digital back-end of the MSM-PF instrument.</u> The MSM constellation may be upgraded to a conical scanner front-end after a demonstration of the performance of the digital back-end on the MSM-PF.

5.3 Working assumptions

This study has focussed on developing a mission concept flying a fully capable instrument that complies with most of the “**Objective**” requirements. This section presents the detailed performance assumptions for preliminary payload sizing. However, a single pathfinder cannot meet a certain number of the “Objective” requirements. Each assumption is presented and justified in Table 14.

When in the next sections, the instrument is referred to as “Objective”, “Breakthrough”, or “Threshold” specification, it is to denote an instrument that complies with the set of requirements **MSM-USR-01 / MSM-USR-02 / MSM-USR-03 / MSM-USR-06 / MSM-USR-07 / MSM-USR-11** of that category. These requirements intrinsically depend on the instrument design and much less on the mission design (e.g., orbit, ground station network or platform capabilities).

MSM-USR-10 / MSM-USR-12 / MSM-USR-13 also stem from intrinsic instrument design but have not been considered in detail in this conceptual study.

Table 14: Working assumptions for the MSM-PF instrument sizing.

ID	Parameter	Objective-O	Breakthrough-B	Threshold-T	Notes
MSM-USR-01	Spectral Bands	50-70 GHz, 90 GHz, 183 GHz, Plus: 118 GHz, 150GHz Plus: 31.4 GHz,36-7 GHz, 23.8 GHz, 19 GHz OR: Complete spectral coverage between 19 and 183 GHz	50-60 GHz, 90 GHz, 183 GHz, Plus: 118 GHz, 150 GHz	50-60 GHz, 90 GHz, 183 GHz	A detailed design is yet to be developed, but the instrument sizing and mission design were based on the "Objective" requirements.
MSM-USR-02	Number of channels	Approx. 1800	Approx. 1100	Approx. 400	
MSM-USR-03	Spectral resolution v /Δv	5000 (T) 4575 (WV)	2500 (T) 1830 (WV)	1250 (T) 915 (WV)	
MSM-USR-04	Spatial Coverage	Global	Global	Full coverage of Australia, including its surrounding area	The pathfinder's orbit will allow full coverage within a repeat cycle (7 days). See the orbit discussion in section 4.3.
MSM-USR-05	Swath width	>=2200 km (tied to orbit height and viewing geometry)	>=2052 km (tied to orbit height and viewing geometry)	>=1800 km (tied to orbit height and viewing geometry)	The proposed orbit altitude (605.5 km) results in a 1950 km swath width. The operational constellation could be higher (~800 km). See the orbit discussion in section 4.3.

ID	Parameter	Objective-O	Breakthrough-B	Threshold-T	Notes
MSM-USR-06	Noise Level (NEΔT)	≤ ATMS actual * 0.5 for spectrum integrated to ATMS SRF and IFOV	≤ ATMS actual * 0.66 for spectrum integrated to ATMS SRF and IFOV	≤ ATMS actual for spectrum integrated to ATMS SRF and IFOV	See Appendix B for more details on achievable noise performance.
MSM-USR-07	Spatial resolution (footprint)	≤5 km at nadir	≤15 km at nadir for temperature sounding. ≤7 km at nadir for humidity.	≤25 km at nadir for temperature sounding. ≤15 km at nadir for humidity.	Assumed a 10 km resolution throughout this study, acknowledging this requires a detailed design of the antenna. This is relevant to the data budget.
MSM-USR-08	Geolocation accuracy	≤10% spatial resolution	≤ 17% spatial resolution	≤25 % spatial resolution	The attitude knowledge system was sized to determine the spacecraft's attitude within 1 km on the ground.
MSM-USR-09	Viewing Geometry	Up to +/-55°, multiple view angles per ground footprint	Up to +/-55°	Up to +/-55°	The objective requirement requires a conical scanner which was ruled out in section 5.2.2.
MSM-USR-10	Polarization	Low-frequency channels (≤37 GHz) polarised	Single linear polarization changing with scan angle (as ATMS)	Single linear polarization changing with scan angle (as ATMS)	Not discussed in detail in this study.
MSM-USR-11	Spatial sampling	Oversampling (Nyquist at minimum)	Contiguous Footprints	Non-contiguous	A conservative sampling frequency of 200 Hz was assumed.

ID	Parameter	Objective-O	Breakthrough-B	Threshold-T	Notes
MSM-USR-12	Calibration mechanism	2-point calibration -40 to -50 dB return loss from onboard source	2-point calibration -40 to -50 dB return loss from onboard source	2-point calibration	Not discussed in detail in this study.
MSM-USR-13	Calibration accuracy	≤0.2 K	≤0.5 K	≤1 K	Not discussed in detail in this study.
MSM-USR-14	Temporal Refresh	Sub-hourly	≤Every 3 hours	≤Every 6 hours *for single pathfinder, once every 12 hours is acceptable*	The temporal resolution requirement can only be met via a constellation.
MSM-USR-15	Instrument lifetime	7 years	5 years	3 years *for a single pathfinder, a 2-year lifetime is acceptable*	Designed for 3 years, as 5 and 7 years will involve a system redundancy and reliability requirement that is likely, not achievable within the mission's cost and schedule constraints.
MSM-USR-16	Global data timeliness	90% within 1 hour	90% within 2 hours	NRT - 90% within 3 hours 30 mins *for single pathfinder, there is no NRT timeliness requirement*	Designed the communications subsystem to a 90% within 20 min data latency requirement for local data and 1 hour for global data as per the Mission Requirements Document [RD-03]. See section 6.1.
MSM-USR-17	Local data timeliness	90% within 10 mins	90 % within 15 mins	90 % within 20 mins	

5.4 Proposed payload architecture

The MSM-PF instrument collects signals from the scene, processes these signals, and provides a digital output suitable for downlink. To accomplish this, the instrument has several subassemblies, including an antenna to collect the signals from the scene, digital spectrometers to digitize the data into hyperspectral channels, onboard calibration and frequency references, and computing hardware. Recent technological advancements in space-qualified Application-Specific Integrated Circuit (ASIC) processing chips* enables the instrument to meet the frequency coverage, spectral channel, and other requirements in each mission configuration. Figure 19 shows the high-level proposed payload architecture diagram.

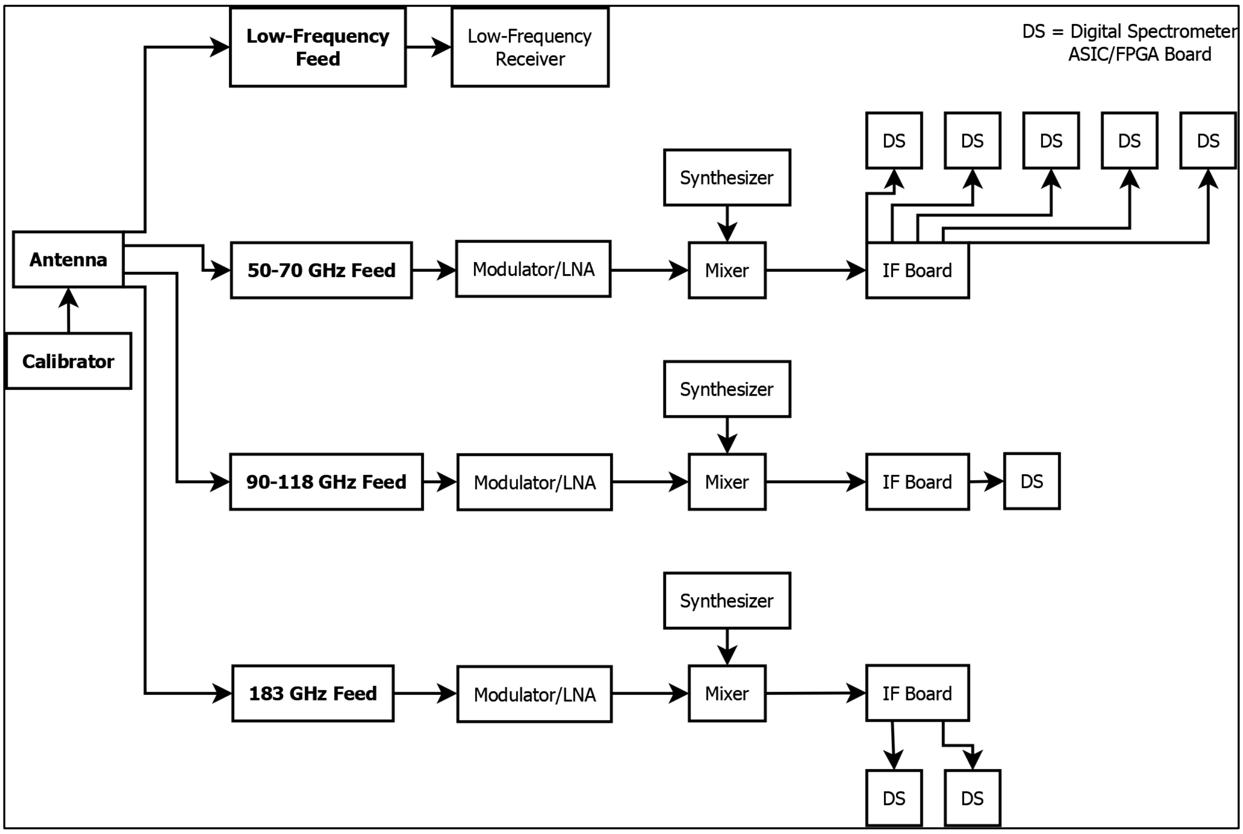

Figure 19: Proposed MSM-PF payload architecture.

Starting at the scene, the sensor payload has a rotating parabolic antenna, an onboard calibration load, several feed horns and analogue front-ends for each frequency band (modulator and LNA). Local oscillator (LO) synthesizers for each spectrometer band enable the signals to be mixed and fed into intermediate-frequency (IF) boards to condition the analogue signals for digitization. Digital spectrometer boards then digitize the signal and form the hyperspectral channels. Finally, computing boards are required to deliver the data (not shown in the diagram).

* In this study, the space-qualified P19800B spectrometer ASIC by Pacific Microchip has been proposed as a possible option for the MSM-PF digital spectrometer. It can process up to 4 GHz of instantaneous analogue bandwidth directly into hundreds of digital spectral channels while consuming 1.6 W of electrical power. Datasheet: http://pacificmicrochip.com/wp-content/uploads/2021/01/Spectrometer%20ASIC%20-%20PMCC-TechProfile_031121_GB.pdf

Note that correlated noise can be a challenge in millimetre-wave receiver systems, and several mitigation approaches are envisaged for the MSM-PF. The digital spectrometer back-end uses a high-performance ASIC and/or FPGA system to digitally divide the received signals into many hyperspectral channels. This means that the passband of each spectral channel is very well controlled by a digital algorithm (such as an FFT and/or a polyphase filter bank), reducing correlated noise due to overlapping passbands. By eliminating many of the analogue signal lines present in an analogue spectrometer, the proposed digital system also eliminates correlated noise due to electrical crosstalk between analogue signal lines.

Correlated noise generated in the receiver front-end from effects such as gain or mixer fluctuations will remain at a level similar to existing systems. An electronic modulation to rapidly switch between observing the scene and a calibrated reference load (i.e. Dicke switching) could potentially reduce these noise sources further. Finally, the large channel count gives a significantly improved space to search for correlated noise in the output data and mitigate it in software analysis on the ground without degradation of the system's performance.

5.5 Preliminary payload sizing

This section proposes a preliminary payload sizing based on the "Objective" requirements, as presented in section 2.3. Appendix B provides additional information on the payload's thermal design and a noise sensitivity analysis.

5.5.1 Power estimate

A bottom-up estimate of the instrument's power consumption was developed for all three instrument configurations (Objective, Breakthrough and Threshold, as defined in section 2.3), with the Objective configuration being carried over for mission budgets. Since many components could be realized using commercial parts, only a 10% instrument-level margin is applied*.

Driven by variations in the frequency coverage requirements, current best estimates are 130.5 W for the Objective specifications, 93.9 W for Breakthrough, and 56.4 W for Threshold, including margin. An itemized breakdown of these figures is presented in Table 15.

* The mission-level power budget presented in section 6.2 accounts for a further 10% uncertainty margin.

Table 15: Summary of power estimate calculations across the three mission configurations.

Subassembly	Objective (W)	Breakthrough (W)	Threshold (W)
Antenna Motor and Calibrator	10	10	10
Modulator	0.2	0.2	0.1
Integrated Mixer Receivers	38.5	38.5	19.3
LO Synthesizers	8.1	8.1	4.0
Digital Spectrometer ASIC Chips	12.8	9.6	6.4
Instrument Computers	15	15	7.5
Thermometers/Housekeeping	2	2	2
Data Storage	2	2	2
Low-Frequency Receiver	30	N/A	N/A
Total without margin	**118.6**	**85.4**	**51.3**
Uncertainty margin (10%)	**11.9**	**8.5**	**5.1**
Total with margin	**130.5**	**93.9**	**56.4**

The Objective configuration has a low-frequency receiver that requires significant power (30 W). The Breakthrough and Threshold configurations do not include this low-frequency receiver, hence the reduced power. The Threshold configuration also has fewer bands and less instantaneous bandwidth than the other configurations, scaling down the power throughout the system.

5.5.2 Volume estimate

Based on the payload expertise available during the study and the commercially available parts used for the power estimate in section 5.5.1, a notional layout for the MSM-PF instrument is proposed in Figure 20. This layout fits in a 350 x 350 x 550 mm^3 volume.

Although the front-end (antenna/calibrator) assembly is yet to be specified or designed, its size is estimated to be 400 x 350 x 350 mm^3 based on a 35 cm antenna aperture.

Based on the orbit altitude (CDF-S-ORB-01), a diffraction-limited 35 cm antenna yields a ground resolution of 10 km at 60 GHz at the nadir, consistent with the nominal 10 km resolution baselined in preparation of this report. Achieving the "Objective" spatial resolution (MSM-USR-07) requirement of 5 km for both temperature and humidity would require a 75 cm antenna, which may exceed the allowable volume envelopes of satellites of the MSM-PF's class. This analysis should be undertaken in future work.

Similarly, commercial parts specifications were used for the back-end to estimate the sizes of the LO synthesizers, computing boards, feeds, and analogue front-end subassemblies[*].

[*] The size estimate of the IF boards was based on the experience of the ASU Mauskopf/Groppi group building similar boards for other applications.

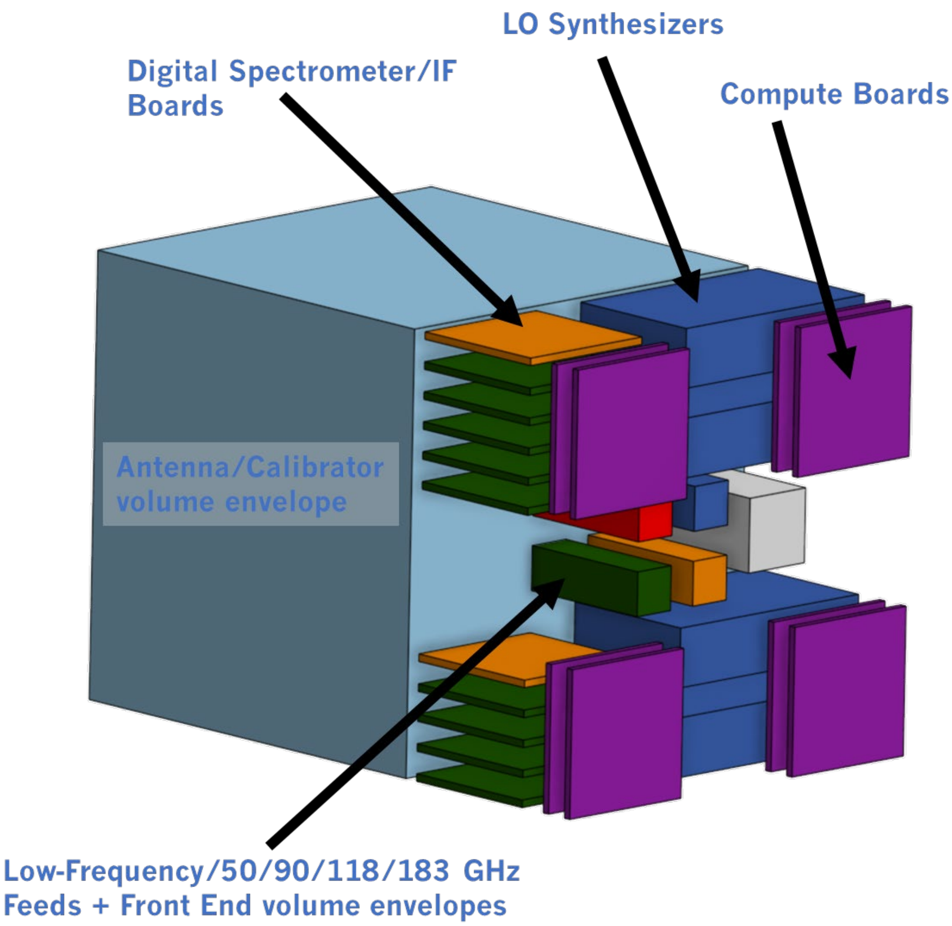

Figure 20: Conceptual layout of the MSM-PF instrument.

This layout did not consider mechanical, thermal, or cable routing considerations, so a significant margin should be held in this size allocation. For this reason, it is proposed to allocate 600 x 400 x 700 mm^3 (ATMS as-built volume) as a conservative volume envelope for mission planning purposes, based both on heritage from ATMS and the need to add margins to the estimate presented in this section. However, it is expected that technological advancements since the development of ATMS may allow an increased capability to fit in the same as-built size envelope.

Note that this envelope was derived assuming the high-capability Objective configuration. It is likely to be smaller for the Breakthrough and Threshold scenarios.

5.5.3 Mass estimate

An accurate payload mass estimate cannot be derived without a detailed design. Therefore, a conservative upper boundary is derived from the survey data in section 3.2.2.

Out of all the surveyed instruments, AWS and BOWIE-M are the only ones to be flown onboard a small satellite of a similar class as the MSM-PF. In principle, replacing either of these instruments' analogue back-end with a digital back-end would be possible, resulting in a lower mass (but higher power) thanks to onboard processors instead of analogue componentry. For this reason, the MSM-PF instrument is expected to be lighter than other comparable (in size) analogue instruments due to the digital back-end.

Table 16 shows the methodology employed to derive an upper boundary for the MSM-PF instrument's mass.

Table 16: Upper boundary calculation for the MSM-PF instrument mass.

Instrument	Mass (kg)	Notes
AWS	42.1	From survey.
BOWIE-M	35	From survey.
MSM-PF upper bound without margin	< 42.1	Assuming AWS's (heavier of the two) analogue back-end is replaced with a new digital back-end.
Uncertainty margin	20%	To account for uncertainty on instrument performance.
MSM-PF upper bound with margin	< 50.5	Used in mission budgets as an upper boundary. It is not a mass estimate.

This study acknowledges that more rigorous analysis is necessary, particularly of whether performance requirements can be met with an AWS front-end. However, only the conservative approach presented above can be proposed at this conceptual stage.

5.5.4 Data rate estimate

Note: The SI convention for prefixes has been assumed for all quantities of data. For example, one kilobit (kb) is one thousand (10^3) bits, not 1 024 = 2^{10} bits. One byte is 8 bits, and one kilobyte (KB) is 8,000 kb.

Using the spectral channel counts, sensitivity, and spatial resolution of each of the three mission configurations, Table 17 presents an estimate of the payload's data rate. The sensor and housekeeping systems are assumed to operate continuously throughout the entire mission.

Table 17: Data rate estimate across the three mission configurations.

Parameter	Obj.	Break.	Thre.	Method of determination
a. Number of Spectral Channels	1800	1100	400	From requirements.
b. Sampling frequency (Hz)	200			Conservative upper bound*.
c. Approximate Per-Channel NEΔT (K)	2.4	1.7	1.2	Equivalent ATMS sensitivity scaled to the MSM-PF's hyperspectral resolution.
d. Quantization (bits)	9†	10	10	$\log_2(300/c) + 2$ 300 K of background with 2 bits of over-resolution as a margin
e. Compression ratio	3:5			A 40% compression was deemed feasible by payload experts available during the study.
f. Housekeeping data rate (kbps)	80			Estimate based on 100 telemetry channels, sampling 16 bits at 50 Hz each.
g. Uncompressed payload data rate (kbps)	3,240	2,200	800	a x b x d. Does not include housekeeping data.
Compressed payload data rate (kbps)	**2,024**	**1,400**	**560**	g x e + f. Includes housekeeping data.

Note that this data rate estimate uses an estimate of the per-channel sensitivity of the mission. The MSM-PF offers a transformational increase in the number of spectral channels over the state-of-the-art ATMS sensor, meaning that an individual spectral channel in this mission has less bandwidth than a channel in ATMS. This inevitably means that even though the overall MSM-PF capability is a major improvement over ATMS, the per-channel sensitivity of MSM-PF is somewhat reduced compared to the per-channel sensitivity of ATMS.

As discussed further in Appendix B, the best comparison between sensors with similar passbands but with a different spectral resolution is to compare the equivalent system temperature of the two sensors. As shown in Appendix B, by leveraging improvements in low noise amplifier and mixer technology, on this crucial metric, MSM-PF delivers an improvement of up to 2.8-12 over the ATMS system.

* One ground resolution at nadir = arctan(10/605) = 0.95 deg. Over the 110 deg total field of view, this equates to 110/0.95 = 116 samples being Nyquist-sampled (as per MSM-USR-11) in 2.254 seconds (MWS scan duration). This corresponds to a sampling frequency of 103 Hz rounded up to a conservative 200 Hz to allow for oversampling.

† The "Objective" configuration's quantization is lower than the two other configurations as the increased number of channels induces a slightly lower noise performance on a per-channel basis – hence a lower number of bits required for quantization.

5.5.5 Payload sizing summary

Table 18 summarises the proposed MSM-PF sizing envelope derived in the previous sections. In this report and for all mission budgets, the "Objective" specifications are assumed.

Table 18: MSM-PF instrument specifications envelope summary.

ID	Specification	Obj.	Break.	Thres.	Method of derivation
CDF-S-PAYL-01	Power (W)	130.5	93.9	56.4	Bottom-up estimate.
CDF-S-PAYL-02	Mass (kg)	50.5			Upper bound based on AWS.
CDF-S-PAYL-03	Volume (mm^3)	600 × 400 × 700			Upper bound based on ATMS.
CDF-S-PAYL-04	Data rate	2,024	1,400	560	Calculated.

6 Preliminary Platform Design

6.1 Communications subsystem

The communications subsystem forms the link between the ground segment and the space segment. It enables the spacecraft to downlink data and telemetry to the ground while enabling the ground segment to uplink commands and control the spacecraft. It can also be used to support attitude and orbit determination. It typically consists of antennas and radios.

6.1.1 Derived mission data and communications requirements

Note: The SI convention for prefixes has been assumed for all quantities of data. For example, one kilobit (kb) is one thousand (10^3) bits, not 1 024 = 2^{10} bits. One byte is 8 bits, and one kilobyte (KB) is 8,000 kb.

Table 19 provides mission data requirements as proposed by this study. These requirements are based on customer requirements and discussions during the workshop.

Table 19: MSM-PF derived data and communications requirements.

ID	Derived data and communications requirement	Rationale
CDF-R-DAT-01	All raw sensor data and telemetry shall be transferred from the space segment to the ground segment.	As per MSM-PRG-02. *Note: It is good and common practice to downlink and store all raw sensor data, particularly for a pathfinder.*
CDF-R-DAT-02	The system shall transmit telemetry data to and receive telecommands from the ground segment in all mission phases (deployment, commissioning, operations, and disposal) and spacecraft attitudes.	TT&C is a basic requirement for satellite operations; communication through the satellite's lifetime is important for the responsible use of space, as per MSM-PRG-04.
CDF-R-DAT-03	The spacecraft shall be able to operate without ground communications for 0.5 days without loss of sensing capability or raw sensor data.	Proposed during the study as a reasonable duration. Older data has significantly decreased usefulness in NWP.
CDF-R-DAT-04	Only authorised users/ground stations shall communicate with the spacecraft for command-and-control and health-monitoring purposes.	MSM-PRG-4, for data privacy and security. Generally, this implies an encrypted and authenticated Telemetry, Tracking, and Command (TT&C) link.
CDF-R-DAT-05	The space and ground segments shall be operated in accordance with the International Telecommunications Union Radio Regulations (ITU RR) and any applicable national regulations where the downlink system is to be operated.	As per MSM-PRG-04. See section 7.7 for more details.

ID	Derived data and communications requirement	Rationale
CDF-R-DAT-06	The communications subsystem shall operate with the spacecraft pointing nadir.	Required to support the instrument imaging pointing nadir at 100% duty cycle—see Section 4.2.5.
CDF-R-DAT-07	All communication links shall be designed with a nominal link margin of at least 3 dB.	A 3 dB link margin is considered typical for LEO communication systems, with a 6 dB link margin desirable where possible[22].

The MSM-PF data volume is readily estimated, given that the instrument is continuously operated as per the concept of operations presented in section 4.2. For the "Objective" instrument configuration, the calculated compressed payload data rate in section 5.5.4 is 2,024 kbps or 0.253 MB/s. Table 20 shows the calculated hourly, daily, monthly and yearly payload data volumes.

Table 20: MSM-PF instrument generated data volumes for various units of time.

ID	Timescale	Uncompressed data volume	Compressed data volume	Unit
CDF-S-DAT-01	1 second	0.42	0.253	MB
CDF-S-DAT-02	1 hour	1518	910.8	MB
CDF-S-DAT-03	1 day	36.5	21.9	GB
CDF-S-DAT-04	1 month (30.5 days)	1111.2	666.7	GB
CDF-S-DAT-05	1 year	13.3	8.0	TB
CDF-S-DAT-06	Mission life (incl. commissioning)	46.5	27.9	TB

The above figures were divided by the compression factor (0.6*) to derive the uncompressed data volumes.

It has been recommended during the study that the spacecraft carries at least the equivalent of 0.5 days of compressed data in onboard storage capacity (CDF-R-DAT-03). This equates to about 10.9 GB, readily achieved with existing onboard storage solutions. Higher storage solutions exist and can be afforded if required.

To transfer data to the ground, a packeting overhead and margin were applied, resulting in a requirement to downlink 26.4 GB/day (see Table 21).

* This compression factor was deemed feasible by the payload experts participating in the study and is based on their experience and expertise. Applicable compression algorithms have not been explored in this study.

Table 21: MSM-PF instrument data downlink requirement

ID	Parameter	Value	Unit	Comment
CDF-S-DDL-01	Data volume per day	21.9	GB/day	Science data compressed. See Table 20.
CDF-S-DDL-02	Packeting overhead	10%		
CDF-S-DDL-03	Required data downlink	24.0	GB/day	= Data generated per day × (1+overhead)
CDF-S-DDL-04	Margin	10%		
CDF-S-DDL-05	Required data downlink with margin	26.4	GB/day	= Required Data Downlink × (1+margin)

Some other key considerations that did not result in a formal requirement are as follows:

- Moving components, such as a mechanically steered antenna, would impose greater demand on the attitude control system and induce additional reliability risks. This study has assumed that this is an undesirable design choice.
- The error performance supported by the DVB-S2[23] telecommunications standard design, equating to a user bit-error rate of approximately 10^{-7}, was assumed as an acceptable trade-off in feasibility and data quality or re-downlink. DVB-S2 has heritage in satellite communications[24], performs close to theoretical limits[25], and off-the-shelf radios supporting it are available.
- As the instrument is a radiofrequency (RF) receiver, the risks of RFI from the communications subsystem to the instrument must be considered as part of the design. A full engineering analysis should be undertaken in future work. However, avoiding using the instrument's receive band for communications would be beneficial, if not necessary (see MSM-USR-01 in Table 4). This could be achieved using optical communications or a different RF band (noting that the most suitable bands are below the instrument's imaging spectrum). For RF systems, any out-of-band emissions, such as harmonics, must also be considered.

6.1.2 Communications subsystem options

A communications subsystem could use either RF or optical communications and either a direct-to-earth link or a link via in-space relays. For RF systems, different RF bands are available for use. Only the RF direct-to-earth was considered for this study, as it is the most technically mature and the only widely available option. Other options may excel in increasing volume and decreasing latency and may wish to be considered for more detailed study, especially as the technologies mature and become more commercially available. An in-space relay system may also be implementable by using the constellation, especially if using a small number of ground stations is desirable (for example, all within Australia). However, it is also beyond the scope of this study.

To link with a spacecraft, a satellite operator can use their own ground station or lease access from a commercial provider. The lease may be an exclusive lease of one or more ground stations or by scheduling time on ground stations shared with other users. The Bureau has proposed that the data be downlinked through a commercial ground-station-as-a-service provider on a shared-access basis.

The Frontier SI Australian industry readiness assessment [RD-04] provides an overview of the commercial ground station providers currently available in Australia.

6.1.3 Payload downlink

6.1.3.1 Preliminary design

The preliminary payload downlink subsystem design detailed in Table 22 was used to show mission feasibility and provide estimates for costings.

Table 23 summarises specifications for this preliminary design, with more details in Appendix A. Requirements CDF-R-DAT-06 and CDF-R-DAT-07 concerning nadir pointing and minimum link margin have been assumed as design constraints. The link was designed to operate at a user data rate of 23.7 Mbps at a minimum elevation angle to the ground station of 20°.

Table 22: MSM-PF preliminary payload downlink subsystem design.

ID	Component	Proposed design	Rationale
CDF-S-DDL-06	Architecture	RF direct-to-earth	Readily available, mature, and suitable. The anticipated cost, risk, and complexity outweigh any benefits.
CDF-S-DDL-07	Ground station network	Commercial ground station as a service, multiple providers globally	See section 6.1.3.2 for more details. A small amount of time over a number of geographically dispersed stations is required to meet latency requirements. Stations from a few commercial providers were examined.
CDF-S-DDL-08	Radio communications band	X-band	Supported by off-the-shelf radios of sufficient data rate, the ITU-RR, and commercial ground stations. It was also considered a reasonable trade of expected available bandwidth and technical difficulty. Does not overlap the instrument's band (see MSM-USR-01), reducing RF interference risks. X-band is typically used for high-volume meteorological polar-orbiting satellites, allowing local direct access with existing infrastructure across the globe.
CDF-S-DDL-09	Spacecraft antenna type	Isoflux, approximately 60° edge of coverage, circular polarised	An isoflux antenna provides reasonably consistent performance across many elevation angles. Used to demonstrate feasibility. Also suitable for a direct-broadcast system, proposed for the MSM. Avoids moving parts. Examples include generation 2 X-Band Helix data downlink antennas produced by Beyond Gravity[26].
CDF-S-DDL-10	Ground station antenna type	5.4 m parabolic dish, circularly polarised	Typical minimum type expected to be available from commercial stations.
CDF-S-DDL-11	Modulation and coding type	DVB-S2 QPSK2/5 SRRC(0.35)	The DVB-S2 standard both performs well and is popular, so expected to be widely supported by existing infrastructure[27]. The exact type was a trade of user data rate and noise performance.

Table 23: MSM-PF space-segment preliminary payload downlink subsystem specifications—requirements for platform and program.

ID	Parameter	Value	Unit	Comment
CDF-S-DDL-12	Power consumption—standby	1	W	Conservative value based on data available for commercially available and suitable radios.
CDF-S-DDL-13	Power consumption—transmitting	20	W	Conservative value based on data available for commercially available and suitable radios.
CDF-S-DDL-14	Mass estimate	1.5	kg	Conservative estimate based on data available for commercially available and suitable radios, antennas, and cabling.
CDF-S-DDL-15	Cost estimate (no margin)	$265,000	AUD	Conservative estimate based on data available on commercially available components.
CDF-S-DDL-16	User data rate	23.7	Mbps	See Appendix A.
CDF-S-DDL-17	Spectral occupied bandwidth	35.1	MHz	See Appendix A.

6.1.3.2 Ground station access analysis

To analyse data volume and latency requirements CDF-R-DAT-01, MSM-USR-16, and MSM-USR-17, ground stations from known ground-station-as-a-service providers Amazon Web Services' (AWS)[28] and Kongsberg Satellite Services' (KSAT)[29] global networks were examined*. An additional station near Alice Springs, Australia, operated by Viasat,[30] was also considered to meet MSM-USR-17 with the preliminary design. While the global latency requirement MSM-USR-16 is not strictly applicable to this pathfinder mission, this preliminary design was designed to meet it. This analysis thus informs the design of the full mission and may also be desirable to implement for the pathfinder mission.

To meet the "Objective" requirement of MSM-USR-16 of 90% of level 1 data to the user within 1 hour, 27 downlink passes per day are proposed (one pass per hour with a margin of three passes). A more frequent downlink than the target period allows additional time for data handling. It also allows for variation of the exact times between downlink periods to account for actual ground station visibility variations.

Carrying out 27 downlinks per day results in an average period of 53.3 minutes between the commencement of each downlink. At each utilised ground pass, 5.6 minutes of downlink time is required to downlink the past 53.3 minutes' of collected data. 5.6 minutes is also close to the mean useful pass length available at ground stations surveyed of approximately 5.3 minutes.

* Exact locations are not publicly available, so locations were approximated based on information given and are considered sufficiently precise for a pre-phase-A study.

There are 5.6 minutes available for well over 90% of 53.3-minute periods, and there are approximately twice as many passes of the required length available out of the surveyed ground stations. This assures that MSM-USR-16 can be met. It should also be noted that conservative ground station performance was assumed. For example, the Viasat Alice Springs station has a 7.3-metre dish, larger than the 5.4 metres assumed.

Ground station coverage over Australia was considered to assess the feasibility of meeting the near-real-time requirement of MSM-USR-17, applicable to the Australian region. Figure 21 and Figure 22 show the coverage of three commercial ground stations identified in the study at minimum elevation angles of 20° and 5°, respectively, listed in Table 24. Figure 21 shows that the satellite would have ground station coverage while overflying over about 90% of the Australian landmass and some coastal regions. In those cases, the payload data could be downlinked almost immediately or otherwise queued up to downlink near the end of the ground station's coverage. Additionally, any instrument data generated during descending passes could be downlinked in near real-time as the satellite passes into areas of satellite coverage.

However, the instrument will sometimes acquire data above the Australian landmass while not overflying it directly due to the large swath width. The half swath width of the instrument corresponds very closely to the difference in 20° and 5° elevation angles from the ground. Therefore, when part of the 20°-elevation coverage area of a ground station is within view of the instrument, the satellite is also within the 5°-elevation coverage of that station. If required, the ground stations' coverage could be extended by reducing the data rate to approximately 4.7 Mbps (the radio is assumed to be capable of such adjustments during operation). The implications of ad-hoc data rate reduction should be explored in future work.

This reduction and the isoflux antenna beam pattern at those angles would compensate for the increased atmospheric and free-space path losses. The data rate is greater than the acquisition rate, meaning that data can be downlinked as it is collected. The 20° elevations cover over 90% of the Australian landmass, so the requirement can be met. Further analysis may show that the 90% requirement can be well exceeded and could also show the extent of coastal areas able to be covered by this near-real-time acquisition. Additional contact time required in downlinking at a lower rate should be minimal, if required at all and is expected to fit within margins, so it has not been separately considered in calculations.

Table 24: Australian ground stations considered for latency analysis over the Australian region.

Location	Provider	Latitude (°, approx.)	Longitude (°, approx.)
Mingenew, WA	KSAT	-29.19	115.44
Alice Springs, NT	Viasat	-23.76	133.88
Sydney, NSW	AWS	-33.87	151.21

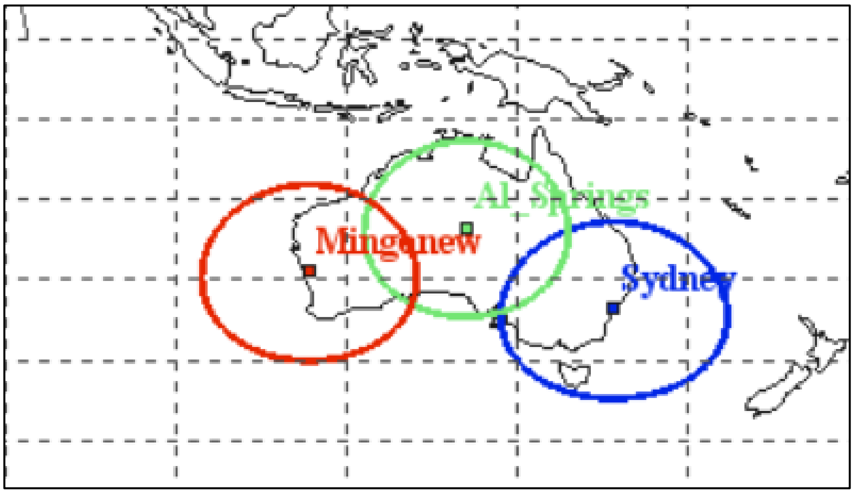

Figure 21: Map showing 20°-elevation coverage of three commercial ground stations in Australia.

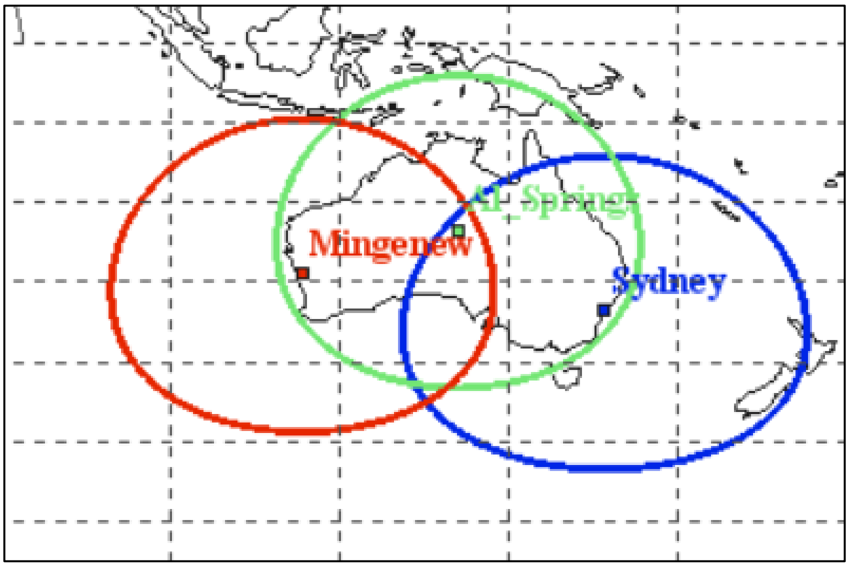

Figure 22: Map showing 5°-elevation coverage of three commercial ground stations in Australia.

Table 25 shows that 149 minutes of downlink time, or approximately 10.5% of an orbit period, is required per day to meet requirement CDF-R-DAT-01 to downlink all data generated by the payload. The ground station availability of 30.9% of the ground stations examined well exceeds the requirement, assuring that all data can be transferred to the ground segment.

Based on publicly available per-minute pricing[31] and including overheads for each pass, ground station access is estimated to cost USD615 per day or USD225,000 per year.

Table 25: MSM-PF ground station access requirements for payload downlink.

ID	Parameter	Value	Unit	Comments
CDF-S-DDL-18	Required data downlink with margin	26.4	GB/day	See Table 21.
CDF-S-DDL-19	Radio user data rate	23.7	Mbps	See Table 23.
CDF-S-DDL-20	Required downlink time	149	min/day	= Required data downlink with margin / Radio user data rate.
CDF-S-DDL-21	Downlink duty cycle	10.5	%	Rounded
CDF-S-DDL-22	Mean number of passes used per day	27	passes/day	See above.
CDF-S-DDL-23	Mean duration of passes used	5.6	min/pass	= required downlink time (based on duty cycle) / passes/day.
CDF-S-DDL-24	Pass overhead per pass	2	min/pass	Assumed two minutes set up and stow for which the provider cannot service any other client, per pass.
CDF-S-DDL-25	Mean billable duration per pass	7.6	min/pass	
CDF-S-DDL-26	Mean billable minutes per day	205	min/day	
CDF-S-DDL-27	Ground station access cost	3	USD/min	Rate offered by example provider.
CDF-S-DDL-28	Cost per day	615	USD	
CDF-S-DDL-29	Cost per year	225,000	USD	

6.1.4 TT&C communications link

This study did not identify any unusual or onerous TT&C requirements. Therefore, it could be assumed that the ground station contact required for TT&C communication would be significantly less and would take place during payload downlink on a different band. The use of dual X- and S-band ground station systems is suggested to meet TT&C communication requirements, especially as the cost to use both bands on such a system would be similar to using X band only as the asset would not be available to other users at the time. The ITU-RR allocates portions of the S-band for satellite uplink and downlink, which are commonly used for that purpose and supported by commercial ground network providers.

Based on this, a fairly typical TT&C radio configuration for a small satellite has been assumed using a commercially available S-band transceiver with a basic patch antenna. For analysis purposes, the Rocket Lab Frontier-S–LEO-ST radio[32] and EnduroSat Commercial S-Band Patch Antenna[33] were used. A separate radio than the payload downlink is proposed to reduce risk. Furthermore, a second radio included in a cold-spare configuration was also assumed for platform redundancy. Table 26 details key parameters.

Table 26: MSM-PF example space-segment TT&C communications subsystem specifications.

ID	Parameter	Value	Unit	Comment
CDF-S-COM-01	Power Consumption—Receiving only	3.5	W	Rocket Lab Frontier-S−LEO-ST radio parameter.
CDF-S-COM-02	Power Consumption—Transmit and Receive	6.8	W	Rocket Lab Frontier-S−LEO-ST radio parameter.
CDF-S-COM-03	Transmit Duty Cycle	1	%	Conservative estimate based on UNSW Canberra Space's experience and typical performance.
CDF-S-COM-04	Mass	1.67	kg	Total for both the active radio and cold spare.
CDF-S-COM-05	Cost (before margin)	$317,200	AUD	Conservative estimate based on data available on commercially available components.

Such a communications link would be designed with requirements CDF-R-DAT-02, CDF-R-DAT-04, CDF-R-DAT-06 and CDF-R-DAT-07 as design constraints.

6.2 Electrical power subsystem

On the MSM-PF spacecraft, the electrical power subsystem (EPS) supplies power to the spacecraft subsystems by managing and distributing power from the solar arrays or the battery.

6.2.1 Derived power requirements

The EPS contains solar panels and batteries managed by a power management and distribution unit (PMAD). The design of the PMAD is assumed to emerge later (in Phase A) and is likely to be sourced as a commercial turnkey product. Table 27 gives the high-level derived requirements of the EPS.

Table 27: MSM-PF electrical power system derived requirements.

ID	Requirement	Driving requirement
CDF-R-PWR-01	The EPS shall sustain all planned operations throughout the mission life.	Concept of operations and MSM-USR-15 (mission design life).
CDF-R-PWR-02	The EPS shall provide adequate voltage to all components.	Not all components require the same voltage. Requirement to be refined as interfaces and component design mature.

A preliminary solar array and battery capacity sizing was achieved through a power budget. The power budget determines the amount of orbit-average power required to support operations. Solar panels must be sized to generate power to supply the energy consumed in each orbit, while batteries should be sized to support worst-case orbit power consumptions, such as eclipse conditions.

The power budget presented in Table 28 was produced using a bottom-up approach. Individual component power consumptions (with margins to reflect uncertainties) were summed by subsystem and combined to form a total orbit-average power consumption figure by operational mode.

- For simplicity, operational modes described by the concept of operations in 4.2 were limited to Payload Acquisition and Simultaneous Payload Acquisition and Downlink. Future iterations of the power budget should include more specific operational modes (e.g., propulsion) currently out of the scope of this conceptual study.
- The duty cycle figures were estimated via orbit simulations for ground station contact.

Table 28: MSM-PF Preliminary power budget.

<table>
<tr><th>Element</th><th>Acquisition (W)</th><th>Acquisition + Downlink (W)</th></tr>
<tr><td>Payload</td><td colspan="2">130.5</td></tr>
<tr><td>Communications</td><td>4.8</td><td>29.1</td></tr>
<tr><td>Onboard data handling (excl. payload data)</td><td colspan="2">4.8</td></tr>
<tr><td>Attitude determination and control</td><td colspan="2">23.4</td></tr>
<tr><td>Total system power, including component margins</td><td>163.4</td><td>187.8</td></tr>
<tr><td>Total system power, including a 10% system margin</td><td>179.8</td><td>206.6</td></tr>
<tr><td>Orbit-Average Duty Cycle</td><td>89.5%</td><td>10.5%[*]</td></tr>
<tr><td rowspan="2">Orbit average power (CDF-S-PWR-01)</td><td colspan="2">182.6 W</td></tr>
<tr><td colspan="2">Including a 10% system margin</td></tr>
</table>

Note that the thermal subsystem has not been explored extensively at this stage but is expected to require minimal power throughout the orbit. See section 6.6 for more details. A similar approach was taken for the onboard data handling system, and future work may suggest slightly higher power consumption values.

However, conservative assumptions were made throughout this analysis, and it is expected that any discrepancies will be absorbed in the margins that have been included. Details of the assumptions can be made available on request.

[*] See CDF-S-DDL-31 in Table 25.

6.2.2 Solar arrays preliminary sizing

The solar arrays were preliminarily sized to estimate their mass and cost.

As calculated in Section 6.2.1, the orbit average power consumed by the spacecraft is estimated to be 182.6 W (including margins). When considering the spacecraft's orbit, a (non-articulated) solar array angled parallel to the spacecraft's orbital plane* would vary in angle to the solar flux between 8 and 32 degrees over a year. Figure 23 shows the predicted solar array to solar flux angle versus time for one year.

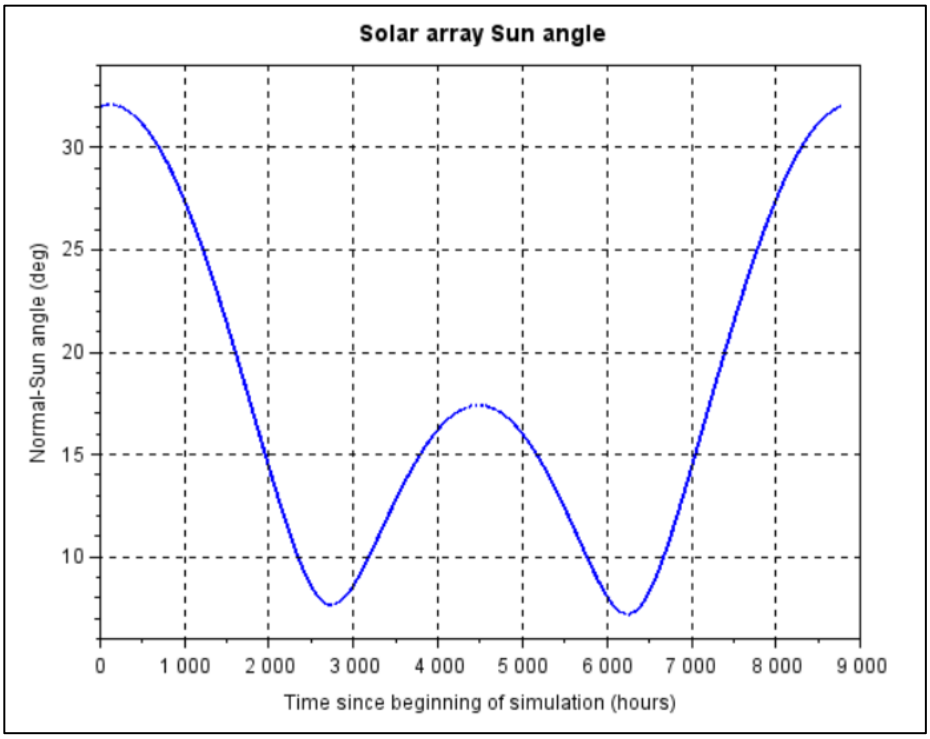

Figure 23: Solar Array Angle with respect to the solar flux throughout one year – 21st December to 20th December.

Factoring in the peak angle of 32 degrees, a solar cell efficiency of 29.5% (Spectrolab XTJ space solar cell[34]), a cell degradation of 2.75% per year, and a cell packing efficiency on the solar array of 85%, the minimum required solar array area was calculated at 0.89 m^2 (CDF-S-PWR-02).

Commercial solar arrays manufacturers such as Spark Wing claim to manufacture solar arrays at approximately 3.8 kg/m^2, with an additional 0.4 kg per deployable panel for hinges and mechanisms[35], indicating that a two-panel solar array – with each panel approximately 0.45 m^2 in size - would weigh about 2.3 kg including a 10% margin (CDF-S-PWR-03).

Solar arrays typically cost EUR1000/W ($1550/W) to produce†, resulting in the flight model solar arrays costing an estimated $540,000.

* A non-articulated solar array is baselined here as the lower risk, lower cost option compared to incorporating articulated solar arrays on the spacecraft. To offset the reduction of power generation at the (southern hemisphere's) summer solstice due to the solar array tilt (maximum of 32 degrees), the size of the array only needs to be increased by 18%. This 18% converts into approximately 0.5 kg of additional solar panel mass and a $130,000 cost to the program, which would easily be exceeded if articulated solar arrays were to be used once the additional engineering effort of modelling, testing, and de-risking the use of articulated solar arrays were taken into account.

† As per UNSW Canberra Space's experience.

6.2.3 Batteries preliminary sizing

Preliminary battery sizing was conducted to support the estimation of spacecraft mass and bottom-up platform costing.

While the proposed orbit results in the spacecraft being in continuous sunlight for most of its mission life, approximately 28% of orbits per year (around the summer solstice) result in the spacecraft entering an eclipse for a maximum duration of 21 minutes during the summer solstice. Considering a worst-case power consumption during this 21-minute eclipse period (Acquiring + Downlinking over ground station and Acquiring for the remainder of the time), 72.5 Wh of energy would be consumed.

Assuming a maximum allowable depth-of-discharge of 30% (battery is drained from 100% to 70%), a battery efficiency of 90% (90% of energy input into the battery is recoverable), an electrical power supply (EPS) efficiency of 95% (95% of energy input into the EPS is available at output), and a battery degradation of 3% for every 3000 cycles, the minimum battery capacity for the MSM-PF is calculated to be 296.4 Wh (CDF-S-PWR-04). These assumptions were selected to provide a conservative battery size; therefore, no additional margin is placed.

Assuming a commercially available battery module[*], the MSM-PF batteries are estimated to weigh approximately 3.5 kg (CDF-S-PWR-05).

6.3 Structure, mass, and volume

The satellite's structure attaches and protects all the other spacecraft subsystems during launch and operations. It is the mechanical backbone of the spacecraft and typically consists of a chassis, articulations, and deployable structures.

6.3.1 Derived structure, volume, and mass requirements

The spacecraft's structural, volumetric, and mass requirements are derived from several sources.

The first requirement to be addressed is typically the upper limit of the spacecraft mass, which is usually determined through iterative analyses of the expected spacecraft mass and suitable launch vehicles[†]. Once a launch vehicle is selected, and the desired insertion orbit is determined, the upper limit of the spacecraft mass (including margins) is defined.

In this report, the Rocket Lab Electron[‡] was the baselined launch vehicle because of the following considerations (detailed in section 7.4.3):

- A dedicated launch was preferred over a rideshare launch, with greater mission flexibility and lower risk in achieving the desired final orbit.
- Rocket Lab's Electron is currently the lowest-cost dedicated launch capability for the expected mass of the MSM-PF spacecraft.

[*] The Saft 4S1P VES16 battery was used in this estimated due to its modular and scalable architecture. Five units are required to meet the minimum battery capacity for the MSM-PF. Other battery modules will yield a slightly different mass, but the precision of this estimate is sufficient for a pre-phase A study.
[†] Launch vehicles are selected based on their mass to orbit capability, costs, availability, allowable insertion orbits, risk, geopolitical factors, launch site facilities, and launch environment.
[‡] UNSW Canberra Space does not have any affiliation with the Rocket Lab company.

- Rocket Lab's Electron has a high launch success-to-failure ratio over many launches, indicating it is a low-risk option.

See Figure 24 for the Rocket Lab Electron's mass-to-orbit performance limits.

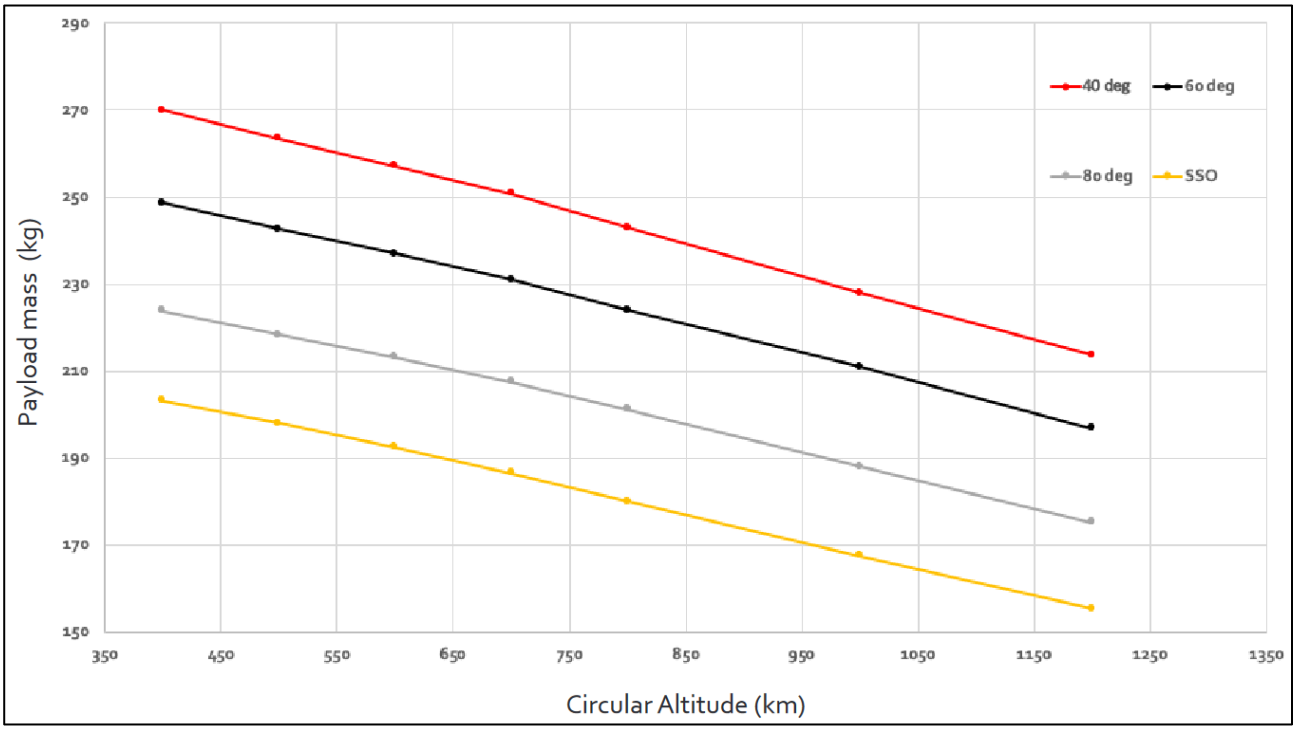

Figure 24: Rocket Lab Electron launch vehicle performance[36].

In the example above, a mass of up to about 193 kg could be launched in the MSM-PF's proposed orbit (605.5 km SSO), this number being inversely correlated to the desired insertion altitude.

The second requirement to be addressed is the maximum allowable spacecraft volume. The maximum allowable payload sizes inside the launch vehicle determine it. Figure 25 shows an example of the allowable internal envelope of a launch vehicle's fairing.

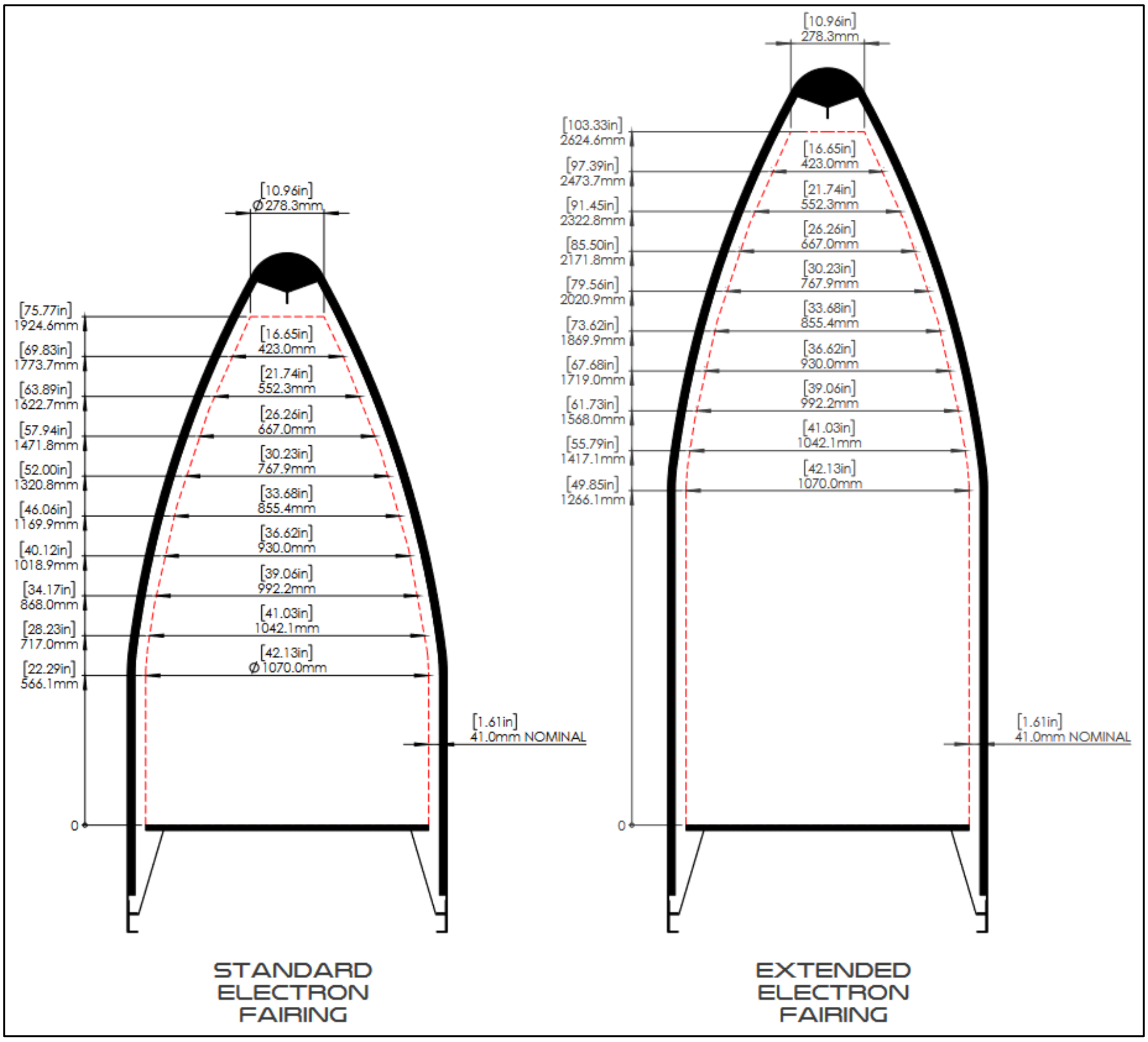

Figure 25: Rocket Lab Electron fairing dimensions[36].

The third requirement is on the spacecraft's structure. The expected launch environment subjected to the spacecraft determines the structural requirements imposed on the spacecraft. These include accelerations, vibrations (including limits on natural frequencies), acoustics, shocks, and pressure. Other structural considerations include compatible separation systems and spacecraft to launch vehicle integration activities. These elements have not been considered in this conceptual study.

Using Rocket Lab's Electron as the baseline launch vehicle (see discussion in section 7.4) and a desired insertion orbit of a 605 km sun-synchronous orbit, the spacecraft has the following high-level mass and size requirements (Table 29):

Table 29: MSM-PF derived mass and volume requirements.

ID	Requirement	Driving requirement
CDF-R-STR-01	The spacecraft's mass shall not exceed 193 kg.	Rocket Lab specification.
CDF-R-STR-02	The spacecraft shall fit within the volume defined by the maximum allowable envelope of the Standard Electron Fairing throughout the entire launch phase.	Rocket Lab specification.

6.3.2 Mass estimation

To estimate the spacecraft's total mass, three approaches were used in conjunction:

1. Scaling from typical EO spacecraft mass fractions,
2. Bottom-up mass budgeting of a bespoke spacecraft design tailored for this mission, and
3. Direct calculation.

The masses of the spacecraft structure, thermal control system, and "other" (launch separation system, balance masses, miscellaneous components, etc.) were scaled using spacecraft mass fractions from typical Earth observation missions[37] since the masses of these systems cannot be determined without a detailed design. These subsystems incur a 20% mass margin.

Bottom-up mass budgeting was used to estimate the masses for electrical power, communications, onboard data handling, attitude determination and control, and propulsion subsystems.

The propellant mass was calculated from the required delta-V and expected thruster-specific impulse (I_{sp}), as discussed in Section 6.4.2.

Each of these subsystems has a resultant mass margin as a result of combining the uncertainties of their component masses. Known COTS components have lower mass uncertainties, typically 5%, compared to unknown components, which can range between 20% to 50%.[*]

Lastly, an additional 10% overall system margin was applied to the totalled masses to account for any unaccounted masses, which resulted in a total dry mass of 152.9 kg and total wet mass of 169.5 kg (CDF-S-STR-01, CDF-S-STR-02).

The subsystem mass estimates, margins, and resultant mass fractions are compiled in Table 30.

[*] Detailed calculations can be made available on request.

Table 30: MSM-PF preliminary mass breakdown.

System	Sub-system estimates		Mass fractions from literature[37]	Resulting mass fraction	Method
	Mass (kg)	Included Margin (%)			
Payload	50.5	20%	31%	36.3%	Upper bound
Structure & Mechanisms	44.0	20%	27%	31.6%	Scaling
Thermal Control	3.3	20%	2%	2.3%	Scaling
Power	10.9	8.1%	21%	7.8%	Bottom-up
Communications	3.6	14.9%	2%	2.6%	Bottom-up
Onboard data handling	3.2	25.3%	5%	2.3%	Bottom-up
ADCS	14.0	10.3%	6%	10.1%	Bottom-up
Propulsion (dry)	4.7	18.3%	3%	3.4%	Bottom-up
Other	4.8	20%	3%	3.5%	Scaling
Total Dry Mass excl. system margin	**139.0**	**17.9%**	100%	100%	Summation
Propellant	15.0	10%	27%	10.8%	Calculated
Total Wet Mass excl. system margin	**154.1**				Summation
Uncertainty Margin	10%				
Total Dry Mass, including margin	**152.9**				Added margin
Total Wet Mass, including margin	**169.5**				Added margin

6.3.3 Volume estimation

The spacecraft volume was approximated by dividing the estimated mass by an approximate uniform density typical of a small satellite.

From surveying the mass and sizes of several small satellites and comparing the results with other reference documents[38], the average uniform density of a small spacecraft is approximately 417.5 kg/m^3. A total wet mass of 169.5 kg results in an estimated spacecraft volume of 0.4 m^3 (CDF-S-STR-03). Assuming a cubic-shaped spacecraft, the length, width, and height would be approximately 0.74 m, with a planform diagonal measurement of 1.046 m.

In comparing these dimensions to the Rocket Lab Electron standard fairing dimensions (Figure 25), this sized spacecraft would slightly exceed the maximum available envelope offered by the launch vehicle fairing. However, considering the Electron standard fairing has an allowable volume of about 1.2 m^3, alternative spacecraft geometries (other than a cube) would easily enable the spacecraft to fit in the standard fairing. Such alternative geometries would be considered as part of a Phase A study.

6.4 Propulsion subsystem

The propulsion subsystem enables the spacecraft to alter its orbit by performing orbital manoeuvres. It typically consists of one or several thrusters and tanks. This section discusses the required manoeuvres, the delta-V throughout the mission's life, and the proposal of appropriate propulsion technologies.

6.4.1 Derived propulsion requirements

This section discusses high-level propulsion subsystem requirements and a preliminary delta-V budget informing the propellant quantity required to meet mission requirements. The delta-V is the change in velocity (in m/s) required to perform a certain orbital manoeuvre. It is analytically calculated using spacecraft properties (such as mass and drag coefficient) and astronomical parameters (such as Earth's mass and solar wind).

The propulsion mode outlined in the concept of operations (section 4.2) briefly outlines the types of manoeuvres expected during the mission's life. The manoeuvres are briefly described below:

- Station acquisition, which is a once-off manoeuvre that raises the spacecraft from insertion altitude to operational mission altitude (if these two altitudes are different), as well as the correction for any orbital plane error.
- Station-keeping, which refers to corrective manoeuvres required to maintain operational orbit throughout the mission life of the MSM-PF spacecraft.
- Evasive manoeuvres, which are manoeuvres required to de-risk conjunction events, such as those caused by space debris or other satellites.
- De-orbit, which is a once-off manoeuvre at the end of the MSM-PF mission that uses onboard propulsion to lower the altitude of the MSM-PF spacecraft to initiate controlled re-entry.

Table 31 proposes a set of high-level requirements for the MSM-PF's propulsion subsystem based on the above manoeuvres.

Table 31: MSM-PF derived propulsion requirements.

ID	Requirement	Driving requirement
CDF-R-PROP-01	The propulsion subsystem shall enable station acquisition during commissioning.	The insertion orbit might differ from the final orbit, and corrections to the altitude and plane might be required.
CDF-R-PROP-02	The propulsion subsystem shall enable station-keeping and orbit maintenance throughout the spacecraft's operational life.	Orbit tolerances are to be defined in future work.
CDF-R-PROP-03	The propulsion subsystem shall enable the safe deorbiting of the spacecraft at the end of its operational life.	MSM-PRG-04 relating to the responsible use of space. A detailed re-entry simulation and risk assessment will further refine this requirement.
CDF-R-PROP-04	The propulsion subsystem shall enable collision avoidance manoeuvres.	Spacecraft safety.

The itemised total of the spacecraft's required delta-V over the mission life is summarised in Table 32. This delta-V budget is calculated for a spacecraft wetted mass of 169.5 kg and yields a propellant mass of 16.57 kg* (CDF-S-PROP-01).

Table 32: Proposed delta-V budget for the MSM-PF.

Manoeuvre	Assumptions and notes	delta-V (m/s)
Station acquisition	Assuming that the insertion altitude is equal to the final orbit altitude (i.e., dedicated launch). A corrective plane change may be required†.	19.8
Station-keeping	This figure depends on spacecraft geometry (cross-sectional area) and solar activity at launch. Assumed maximal solar activity and a cross-section based on volume estimate and solar array sizing.	14.2
Evasive manoeuvres	Assumed 1 m/s per manoeuvre[39] per month over the mission life. Requires further analysis to determine the frequency of these manoeuvres.	42.0
De-orbit	A Hohmann transfer from mission altitude to re-entry altitude (78km‡) is assumed to result in controlled re-entry within a single orbit period.	149.8
Total§ CDF-S-PROP-02		**225.7**

6.4.2 Propulsion subsystem preliminary design

Most propulsion systems available for purchase are based on chemical or electric propulsion technologies. There are several implementations of each, though generally, chemical propulsion is favoured for high-thrust short-duration missions (3-5 years) and requires more mass. Electric propulsion is favoured for low-thrust long-duration missions (10+ years) and uses more power. In this report, this study assumes a chemical propulsion system. The reasons for this are:

- It is unknown at this stage whether safe, controlled de-orbiting can be achieved with an electric propulsion system due to the low thrust afforded by these.
- Evasive and de-orbit manoeuvres are best performed by high-thrust systems[40]. On average, high-TRL green propellant systems yield about 120 N of thrust, while most electric systems yield 20-100 mN[41].

* A specific impulse figure of 285 s was used in the rocket equation for this calculation and was baselined on that of the Dawn Aerospace B20 thruster (See https://www.dawnaerospace.com/products/satdrive#b20)

† Orbit insertion inclination error is based on a +/- 0.15 deg figure quoted in RocketLab Launch Payload User Guide 6.5 (See https://www.rocketlabusa.com/assets/Uploads/Rocket-Lab-Launch-Payload-Users-Guide-6.5.pdf)

‡ NASA Orbital Debris Program Office considers 78km to be the nominal spacecraft breakup altitude (See https://orbitaldebris.jsc.nasa.gov/reentry).

§ No margin is usually included in delta-V budgets as it is an analytically calculated quantity. However, "Gülgönül, S., & Sözbir, N. (2018). Propellant Budget Calculation of Geostationary Satellites." recommends accounting adding a 2% margin to account for "dispersion burns". We do not account for this at this conceptual stage.

- The mass savings an electric propulsion system afford are outweighed by the greater power consumption required. The current analysis estimates that a chemical propulsion system for MSM-PF (dry weight plus propellant) weighs 21.3 kg and consumes virtually no power (except during the short ignition phase). A suitable high-TRL electric turnkey solution* weighs 6.7kg and consumes 0.25W at rest (warm) and 55W when firing. This electric propulsion alternative represents an 8% spacecraft mass saving but a drastic increase in power consumption (55W firing throughout the orbit is 30% of 182.6W orbit-average power), which will cause battery and solar array mass to increase and, in turn, reduce spacecraft mass savings.
- It is assumed that high-TRL products are favoured for the MSM-PF mission, where possible. As chemical propulsion technology has a longer flight heritage and lower development costs than electric propulsion, it is accepted practice to favour chemical propulsion systems when the total impulse is manageable for short-duration missions[41], such as the MSM-PF.

For a chemical propulsion system, green propellants should be favoured as they offer greater impulse figures than traditional monopropellant hydrazine fuels, are more likely to comply with incoming environmental standards and are relatively stable during storage[41].

6.5 Attitude determination and control subsystem

The Attitude Determination and Control Subsystem (ADCS) enables the spacecraft to rotate itself in the vacuum of space. It provides the accurate pointing required by critical elements such as the payload, the communications antennas and solar arrays. It typically consists of actuators and sensors. Actuators include reaction wheels and magnetic torquers. Sensors include star trackers, magnetometers, Earth Horizon Sensors (EHS), and inertial measurement units.

6.5.1 Derived pointing requirements

The MSM-PF spacecraft pointing requirements are primarily driven by the payload requirements and secondarily by communications subsystems requirements (antenna pointing). At this stage, the communications subsystem is expected to not introduce more stringent pointing requirements than the payload. The derivation work assumes the orbit's altitude proposed in section 4.3.2, i.e., an altitude of 605.5 km.

Some requirements will be derived from other mission requirements and spacecraft properties as the design is refined. At this stage, the pointing accuracy is not unusually constrained, particularly thanks to the large instrument swath. Implications on the ADCS of the continually rotating payload antenna have not been considered at this stage and should be explored in future work.

Table 33 shows the MSM-PF derived pointing requirements.

Table 33: MSM-PF derived pointing requirement.

ID	Specification	Value	Derived from

* The baseline electric propulsion system in this example is the Bradford Space Comet-8000 integrated propulsion system designed for small satellites (See https://www.satcatalog.com/component/comet-8000/)

CDF-R-ADCS-01	Absolute Pointing Knowledge	0.1 GSD 0.09 deg 5.7 arcmin	MSM-URS-08-O. Requirement to geolocate samples to an accuracy greater than a tenth of the GSD (10 km). *Note: this is largely attainable with a star tracker, which typically allows a pointing knowledge in the order of 10 arcsecs.*

6.5.2 Reaction wheels preliminary sizing

Reaction wheels were sized to achieve both a minimum slew rate and minimum slew acceleration of the spacecraft deemed suitable for the mission. The values were calculated as per the following:

- The minimum required slew rate was defined by assuming the spacecraft should take no longer than 5 minutes to rotate itself around any of its axes 360 degrees, resulting in a minimum slew rate of 1.2 deg/s. This is comparable to other small spacecraft[42].
- The minimum slew acceleration was defined by assuming the spacecraft could reach the minimum slew rate in either rotational direction from zero angular velocity within 5 seconds, equating to a minimum slew acceleration of 0.24 deg/s^2.

With the spacecraft mass and size approximated to be 169.5 kg and 0.74 m along each side, respectively (see 6.3.2 and 6.3.3 for derivations), and assuming a uniform spacecraft mass, the minimum required angular momentum and torque generated by the reaction wheel assembly were calculated to be 0.323 N.m.s and 0.065 N.m respectively.

Assuming the reaction wheel assembly uses a pyramid configuration[*], and including a 150% angular momentum margin[†] and 50% torque margin, the minimum required angular momentum and torque for an individual reaction wheel are 0.517 N.m.s and 0.062 N.m, respectively.

When surveying several COTS reaction wheels, Rocket Lab's RW 1.0 reaction wheel was selected to provide a baseline mass for estimating the spacecraft mass.

Table 34: Baselined reaction wheels.

ID	Specification	Minimum Required	Rocket Lab RW 1.0
CDF-S-ADCS-01	Angular Momentum (N.m.s)	0.517	1
CDF-S-ADCS-02	Torque (N.m)	0.062	0.1

[*] In a pyramid configuration, the combined momentum storage and output torque of the four reaction wheels is approximately 1.56x the individual momentum storage and output torque of each reaction wheel.

[†] The 150% angular momentum margin accounts for a reaction wheel – which typically is never at zero RPM – to output the required angular momentum just before reaching maximum RPM. Assuming the reaction wheel nominally spins at 50% of its maximum RPM, then the required 0.517 N.m.s angular momentum output can only be achieved within the remaining 50% RPM. With an additional 1.25x margin, the total margin equates to 150%.

6.6 Thermal control subsystem

In a general sense, the primary thermal requirements for any spacecraft design are:

- Keep every component within their non-operating temperature limits (including margins) when the component is not operating.
- Keep every component within their operating temperature limit (including margins) when the component is operating.

In addition to the above, further thermal requirements may include thermal stability requirements that limit the rate at which a component's temperature can vary with time and thermal gradient requirements that limit the change in temperature across a component's length.

At this stage of the mission design, it is expected that the spacecraft platform will require a relatively simple thermal control system, as the thermal loads on the spacecraft are relatively low and constant. In fact, as detailed in section 4.3.2, the preferred orbit is an SSO with a 05:30 LTAN with the spacecraft constantly nadir pointing. This combination of orbit and attitude results in a near continuous illumination of one side of the spacecraft, except for eclipse periods around the summer solstice. This illumination environment allows for a simple spacecraft configuration with solar arrays mounted or deployed on the illuminated face of the spacecraft and thermal radiators on any other face that does not view the Earth.

The spacecraft is expected to continuously consume 181.6 W on average throughout its orbit (approximately equal to the heat it must continuously radiate). Therefore, it only requires fixed radiators and thermal conduction mechanisms to transport heat inside the spacecraft to the radiators. Assuming a radiator operating at 30°C with an emissivity of 0.95, the required radiator size is approximately 0.4 m^2 (CDF-S-THERM-01). This radiator area will likely be divided among individual radiators over the spacecraft to ease integration. The payload having its radiator will simplify its development, testing, integration with the platform, and possibly operations.

As the mission design matures, more detailed considerations of thermal requirements will need to be undertaken.

6.7 Command and data handling subsystem

The Command and Data Handling (CD&H) subsystem is the centre of the suite of computing systems that supports the onboard processing activities of the spacecraft.

- Onboard processing activities and behaviours are defined in flight software. Users configure flight software, and performance is limited by available onboard computing resources, avionics, and code efficiency.
- Onboard computing resources should be selected according to specific MSM-PF onboard processing requirements, which are not known in detail at this stage. Different computing options maximise various metrics, such as parallelism for data processing, often trading some resources, such as power consumption.
- Further, as the MSM-PF concept of operations continues to evolve, certain processing tasks might be delegated to ground-based infrastructure.

An integrated computing solution can be based on different types of processing units.

- CPUs provide sequential instruction execution for general software applications. All integrated computing solutions are expected to have at least one CPU resource.
- GPUs and VPUs are ideal for parallel instruction execution for image processing and artificial intelligence. When compared to a CPU which steps through a sequence of instructions from one clock cycle to the next, a GPU divides an equivalent instruction sequence into multiple parallel sub-tasks and executes them simultaneously. For this reason, GPUs are faster for parallelised tasks than CPUs but consume much more power.
- FPGAs are integrated circuits configured in software and are useful for rapid redefinitions of connections between components such as clock sources, amplifiers, and embedded CPU cores.

At this stage, the MSM-PF’s command and data handling subsystem and its requirements have not been considered in detail and should be examined in future work.

7 Mission Implementation

This section discusses implementation and procurement options for the mission's space segment.

7.1 Platform

The Frontier SI Australian industry readiness assessment [RD-04] provides an overview of the Australian platform procurement options.

7.1.1 Description

The spacecraft platform provides the necessary functions of the spacecraft that are not specific to the payload. These functions are typically divided among the spacecraft subsystems and their subsequent components, as shown in Table 35.

Table 35: Spacecraft platform subsystems and associated components.

Subsystem	Components
Attitude Determination and Control	▪ ADCS Computer ▪ Coarse Sun Sensors/Earth Horizon Sensors ▪ Magnetometers ▪ Gyroscopes ▪ GPS ▪ Star Trackers ▪ Reaction Wheels ▪ Magnetorquers
Structures & mechanisms	▪ Structure ▪ Separation System ▪ Hold-Down Release Mechanisms (HDRMs) ▪ Radiation shielding
Thermal management	▪ Heaters ▪ Radiators ▪ Insulation
Power management	▪ Solar arrays ▪ Batteries ▪ Power Management and Distribution Unit
Onboard Data Handling	▪ Flight Computers and Software
Communications	▪ Radios ▪ Antennas
Propulsion	▪ Thruster ▪ Tanks and propellant
Other	▪ Harnessing (electrical & signal) ▪ Balance mass

Provision of the platform is usually achieved via one of the two following methods:

- Purchase of an off-the-shelf integrated platform with flight heritage, onto which the instrument and mission-specific hardware are integrated, or
- A custom-built platform designed and assembled from primarily flight-proven subsystems, most likely with a bespoke structure.

The former option typically costs less and has lower inherent risk due to its flight heritage, but it may not meet all the payload's requirements. Conversely, the latter option will typically meet all of the payload requirements, as it has been custom-built to do so, but the custom-build may incur higher risk due to the lack of flight heritage and a higher cost.

7.1.2 Integrated Platform Implementation

From surveying current Commercial Off-The-Shelf (COTS) satellite platform offerings, it was found that several COTS small satellite platforms could potentially meet or exceed MSM-PF's requirements. Details of these platforms are shown in Table 36.

Many platforms providers have, or likely have, options to customise them for mission needs. Should the preference be to use an integrated COTS platform, the tender process should involve engaging with a shortlisted group of COTS spacecraft manufacturers to tailor the spacecraft to suit the instrument to best achieve the mission objectives.

Table 36: Available COTS integrated small spacecraft platforms.

Bus	Manufacturer (Country)	Power	Volume Assessment		Communications	Pointing	Propulsion
			Mass (kg)	Volume (mm³)			
MSM-PF requirement		130.5 W	50.5	600 x 400 x 700	Analysis in this report: 23.7 Mbps	Control: - Knowledge: 0.09°	Orbit dependent.
ARROW	Airbus (USA)	210 W OAP (payload)	100	480 x 520 x 520	Various options available, up to 1.6 Gbps	Control: 0.08° (1-sigma) Knowledge: 0.07° (1-sigma)	Electric. Max delta-V: 800 m/s
BCP-100, ESPA-G	Ball Aerospace (USA)	330 W OAP (payload)	80		200Mbps	Control: 0.03° (3-sigma) Knowledge: 0.03° (3-sigma)	Electric & chemical (incl. green) options
LEOS-100HP	Berlin Space Technologies (Germany)	300 W av. (2kW peak)	50 – 75	600 x 600 x 600	X-band: 640Mbit/s		Electric propulsion
X-Sat, Saturn Class	Blue Canyon Technologies (USA)	444 W (2x solar arrays)	70	762 x 762 x 1016		Control: ±0.002° (1-sigma)	Multiple electric & chemical systems are available
Australis	Inovor Technologies (AUS)	>150W (payload)	>65	~400 x 400 x 400	X-band available	Control: <0.05° Knowledge: <0.02°	
MP42	Kongsberg Nanoavionics (USA)	238 W OAP (triple deployable solar arrays)		490 x 490 x 350 *extendable depending on payload mass properties*	S-band: 10Mbps Tx / 128kbps Rx X-band: 1Gbps	Control: 0.05° Knowledge: 0.01°	Chemical: EPSS C2 / C3 Max. total impulse: 1700 / 4000Ns
MP42D	Kongsberg Nanoavionics (USA)	378 W OAP (triple deployable solar arrays)		740 x 730 x 500 *extendable depending on payload mass properties*			
SSTL-Micro	Surrey Satellite Technologies (UK)	63W OAP (payload)	<65	450 x 340 x 340	S-band: 2Mbps Tx / 600kbps Rx X-band: 140Mbps	Control: <0.1° Knowledge: <0.05°	Electric, xenon

7.1.3 Bespoke platform implementation

This section discusses various staffing and design approaches that can be adopted to realise the main subsystems of a bespoke platform product that perform the subsystem functions listed in Table 35. The UNSW Canberra Space group's experience with M2 demonstrated that system integration and emergent system behaviours were significant sources of risk in a bespoke platform implementation. For this reason, rigorous systems engineering practices and high-TRL components should be favoured in future Phase A analyses so that uncertainties introduced by experimental components do not needlessly reduce whole-of-system reliability.

Attitude Determination and Control System

The Attitude Determination and Control System (ADCS) subsystem senses and controls the spacecraft's attitude (position and orientation) state. During the lifetime of a satellite, its attitude is continuously affected by disturbances in the form of gravity gradients, solar radiation pressure, magnetic fields and aerodynamic torques. These disturbance torque fields need to be reacted against to maintain satellite pointing requirements.

The ADCS design follows an iterative step-by-step control systems question-and-answer process to determine types and quantities of ADCS actuators and sensors based on operational control modes, pointing accuracy and processing requirements[43].

Most modern space missions use 3-axis control to manage angular momentum with magnetorquers and reaction-wheels for all three axes of rotational control[*]. Spacecraft and orbit geometries determine the attitude sensors selection and are a combination of star trackers, magnetometers, gyroscopes, and sun/earth horizon sensors. ADCS systems also house their own computer (distinct from the onboard computer under the Command and Data Handling subsystem) that forms the control logic layer that processes sensor data and drives actuator devices as part of a coherent control system.

There are limited available turnkey ADCS solutions for the MSM-PF weight class. Though integrated and bespoke ADCS solutions cost for microsatellites and CubeSats can be expected to be similar[†], the size and additional complexity of a SmallSat mission may encourage a mission sponsor to seek a more bespoke ADCS solution.

Bespoke ADCS subsystem design is a substantial staffing decision as ADCS design is a specialised engineering discipline. ADCS engineers are a subset of Control Systems Engineers who often have specialised in a mechanical, electrical, or related electro-mechanical Engineering discipline such as Aerospace engineering. Broadly, an ADCS engineer is responsible for implementing the ADCS as a control system with control modes, disturbance environment coping mechanisms and interfaces that can integrate with the rest of the spacecraft at a systems and operations level. Ideally, qualified ADCS engineers should have continuity of involvement from Phase A concept development through to the end of commissioning.

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[*] Actuation in a single rotational dimension is usually achieved using a reaction wheel paired with a magnetorquer (for desaturation). To prevent unwanted spacecraft tumbling, an ADCS transfers excess angular momentum from the spacecraft to reaction wheels on each axis of rotation. To prevent reaction wheels from exceeding their speed limits (saturation), magnetorquers provide a counter-torques on appropriate spacecraft rotational axes that the ADCS transfers to the wheels to slow them down.

[†] This claim is based on UNSW Canberra Space's own experience with ADCS development for the M2 mission, which was delivered in a year. The M2 ADCS subsystems were developed in-house by a dedicated ADCS Engineer. The cost of hiring an in-house ADCS engineer, plus development costs and time, were similar in magnitude to the cost of procuring a turnkey model from say, Blue Canyon Technologies.

Command and Data Handling

The Command and Data Handling subsystem (CD&H) exists as avionics (processors, integrated components, and platform interfaces) that manage spacecraft tasks specified by user input or scheduled tasks, usually via a central on-board computer (OBC). CD&H avionics behaviour is defined in flight software, which is stored and executed from OBC memory.

Design of the CD&H subsystem begins with a Requirements flow-down that decomposes mission objectives into low-level computing requirements. Each feature has a minimum set of logical features and controls (e.g., re-programmability, auto-timeout).

Logical features and control requirements might be met in hardware or software. These low-level requirements are organised into different technology layers associated with their design (or purchase) requirements. Common layers are the hardware, firmware and application layers. More layers might be added as the granularity of the design increases.

Flight software should be expected to be updated throughout the entire mission[*]. For this reason, software quality control practices and change management, such as version control, should be adopted as soon as possible. Development boards and representative engineering models for prototyping and integration testing should be considered as the MSM-PF concept is refined.

Development of the CD&H subsystem involves significant embedded systems development. Most qualified Embedded Systems Engineers hold Electrical, Mechatronics or Computing-related bachelor's degrees and have experience in hardware or low-level software or electronics development. Embedded Systems Engineers should be involved from concept formation in Phase A through to closeout in Phase F. An embedded systems engineer can expect to continue developing new functionality or improving existing software throughout the life of the MSM-PF mission.

Electrical Power Subsystem

The electrical power subsystem manages on-board power storage, generation, and distribution to different avionics as the spacecraft experiences various operating conditions. The physical components of this subsystem are the batteries, solar arrays, and power management (PMAD) electronics. Batteries and solar arrays are usually purchased as integrated turnkey commercial products. PMAD units can be purchased as high-TRL turnkey integrated units or implemented as bespoke solutions. The first step in PMAD design is to consider power management requirements. This step establishes a spacecraft power supply platform at the boundaries of the batteries and solar arrays that are safe for avionics. The second step in PMAD design is to consider power distribution. A load profile established in the early PMAD design process should inform what fault protections, switching mechanisms and cabling[†] should be present.

To implement an electrical power system on a bespoke MSM-PF platform, an electronics engineer should expect to be involved from Phase A concept development to integration, test and launch in Phase D. An electronics engineer may also be occasionally involved in on-orbit troubleshooting activities between Phase E operations and closeout in Phase F, to rule out hardware subsystem failures. A qualified electronics engineer would have specialised in Electronics from an Electrical Engineering background or similar. Such engineers should be expected to be lead circuit and board designers and electronics assembly/integration/testing leads for the MSM-PF mission.

[*] The software update process is a means of adding functionality, fixing issues and recovering systems trapped in bad states.
[†] Cabling can be challenging design task. Cables are relatively heavy, and present thermal and signal interference problems when low-voltage, high-current electronics are involved. Cable management issues can snowball when minimum bends and strains are enforced.

Payload Communications

The MSM-PF spacecraft's payload communications subsystem (or science data downlink subsystem) facilitates science-related data transfers (or downlink) from the spacecraft to ground station receivers. Transmission of science-related data using the payload communications subsystem is specifically in the direction from the spacecraft to a ground station. The payload communications radio is separate from the TT&C radio on the MSM-PF spacecraft, and transmission events from both radios may occur concurrently.

The design approach and implementation of payload communication subsystem transmit radio begins with an accounting for the top-level requirements and constraints, a baseline selection of a ground station network and a communications link design and budget.

For an onboard RF system to be implemented, an RF engineer should be engaged from Phase A to the end of commissioning. A qualified RF engineer would have an Electrical Engineering or related degree and ideally be comfortable in radio design activities, including RF systems assembly, CAD simulation software usage, integration and testing. During Phase E operations, the RF engineer may be required to troubleshoot the spacecraft's link or other communications issues. An RF engineer should also be expected to work as part of a multidisciplinary team due to the overlap of the payload communications subsystem into software and hardware interfaces with the payload.

Tracking, Telemetry and Control

The Tracking, Telemetry and Control (TT&C) subsystem on the MSM-PF spacecraft facilitates non-science data transfers to and from the spacecraft and ground station receivers. Non-science data includes operations tasking (commands), spacecraft health monitoring data (telemetry) and subsystem software updates. The TT&C radio is considered separate from the payload communications radio on the MSM-PF spacecraft. Transmission events from both radios may occur concurrently.

Similar to the design approach and implementation of payload communications, the TT&C-centric design process of a transmit and receive radio system begins with reviewing top-level engineering requirements and constraints, followed by a baseline selection of a ground station network. This is followed by a TT&C link design and budget that is refined as the spacecraft design matures.

For an onboard TT&C RF system to be implemented, an RF engineer should be engaged from Phase A to the end of commissioning. Depending on the mission's complexity, this can be the same engineer(s) described in the payload communications subsystem discussion. As with the payload communications subsystem, the TT&C RF engineer is directly involved with the design, simulation and testing of the TT&C subsystem, as well as on-orbit troubleshooting and fault tree analysis activities post-launch if needed. Particularly for the TT&C subsystem, the RF engineer should also be expected to work with the CD&H engineer(s) and, in general, as part of a multidisciplinary team due to the overlap of the TT&C subsystem into MSM-PF software and hardware interfaces.

Propulsion

The MSM-PF propulsion subsystem performs the propulsive manoeuvres described in section 6.4.1. As chemical propulsion has been proposed, the physical components of the propulsion subsystem will include thrusters, fuel tanks and associated fittings.

The design and implementation of a propulsion system begin with a delta-V budget to estimate the amount of fuel required by the mission. This is true for both bespoke and commercially purchased platforms. The physical components (fuel tanks, thrusters, and fittings) are expected to be purchased as commercial products. For a bespoke platform implementation, the propulsion subsystem implementation work should focus on refining the delta-V (fuel) budget and integrating the physical components with other spacecraft avionics.

A propulsion engineer should lead the implementation of the propulsion subsystem. Propulsion engineers have qualifications in Aerospace, Mechanical or related fields of Engineering and should expect to be heavily involved in the spacecraft development processes from Phase A to Phase D. Duties of a Propulsion engineer will focus on integrating and testing the chemical propulsion components into the spacecraft during assembly. They may also contribute to the mission's concept of operations and manoeuvres planning.

Structure and Mechanisms

The structure and mechanisms subsystem of MSM-PF spacecraft will likely comprise the following major components that serve the following functions:

- Frame & panels, onto which the other subsystems mount. Panels also provide radiation shielding for internal components as well as a degree of debris shielding
- Separation systems, to enable the spacecraft's structure to attach to and release from the launch vehicle
- Debris shielding, to protect the spacecraft's internal components from micro debris
- Hold-Down Release Mechanisms (HDRMs) to stow and release deployable structures on command

The physically central nature of the mechanical subsystem requires multiple design factors to be considered simultaneously. Some of these factors include the overall physical configuration of the spacecraft, which requires taking into account illumination of solar arrays during non-eclipse periods of the orbit, thermal radiator FOVs (preferably of deep space), FOV of sensors (e.g., instrument, star trackers, sun sensors, etc.), placement of propulsion systems and clearances for their exhaust plume(s), placement of internal components to ensure correct mass distribution as well as efficient thermal management, mounting of the spacecraft to the launch vehicle, the handling and manipulation of spacecraft during ground activities, and the assembly process.

A mechanical engineer should lead the implementation of the structure and mechanisms subsystem. Ideally, a qualified mechanical engineer for a bespoke MSM-PF platform should have a background in Mechanical and Aerospace Engineering. This role must work closely with the payload systems, thermal, electrical, RF, and propulsion systems disciplines to manage the physical spacecraft interfaces and configure the spacecraft most optimally. The mechanical engineering lead for the structure and mechanisms subsystem should be involved as early in the mission design as possible and is most active from Phase A conceptual design to launch in Phase D. Their role will require extensive mechanical design, testing and coordination with a multidisciplinary team.

Thermal Control Sub-System

The thermal control subsystem maintains components within their operating or non-operating temperature ranges. Thermal control subsystems can range in complexity from a simple passive design to a more complex active design. Both passive and active designs typically incorporate radiators, thermal insulation (typically Multi-Layer Insulation, MLI), thermal straps and/or heat pipes, heaters, and temperature sensors (thermocouples, etc.), with active systems utilising additional components such as adjustable louvres over their radiators, thermal conductor switches, and/or pumped fluid loops.

The thermal control subsystem is designed to respond to the internal and external thermal loads. As a result, aspects of the spacecraft configuration must be developed in concert with the thermal control system. During the development of the thermal control system, extensive thermal simulation of the spacecraft is usually undertaken. Thermal testing is conducted within thermal cycling vacuum chambers, where heat loads from the sun and Earth and heat sinks of deep space can be replicated.

Due to the specific environment and design changes with spacecraft, a mechanical engineer specifically trained in spacecraft thermal engineering should lead the thermal control subsystem development. The thermal engineer should work closely with the structures and mechanisms lead so the spacecraft can be configured to optimally support the thermal management of the spacecraft and instrument(s). Thermal engineers will usually be required from the start of Phase A through to the end of commissioning of the spacecraft to ensure the spacecraft's thermal control system is functioning properly. Their work will require extensive thermal design, simulation, and testing.

7.1.4 Recommended approach for the MSM-PF

As with any project, a balance must be reached between the desired capability (or scope of work) and its inherent costs and risks. This balance must be struck for the spacecraft bus between an existing COTS integrated bus (pre-defined capability, with lower cost and lower risk) and a bespoke bus (tailored capability, with higher cost and risk).

For this mission, the number of COTS integrated platforms that meet the support requirements for the current payload design lead to the recommendation of procuring an existing COTS platform. These platforms have already been developed and have gained flight heritage, resulting in lower costs and risk. Without a deeper analysis of each COTS platform, recommendations on a particular platform or a short-list of suppliers cannot be made at this stage. Instead, it is recommended that an open-tender process be undertaken and responses be evaluated on their ability to meet the mission requirements. This open-tender process should allow the bidding of international organisations, as international spacecraft developers have existing and almost suitable spacecraft with flight heritage.

At the time of writing, no Australian manufacturer has launched nor operated a small spacecraft with bus capabilities close to that required for the MSM-PF mission. However, from engaging with a few Australian spacecraft manufacturers as well as noting the growth rate of the Australian space industry, with sufficient support, there is reasonable confidence that the Australian space industry will be able to provide a spacecraft bus capable of meeting MSM-PF's bus requirements within the next 5 years. Suppose this capability is developed in time, and the costs and risks associated with such a bus are acceptable. In that case, purchasing an Australian bus may be the preferred option as it would potentially allow for easier, more responsive, and local payload integration, which is required to be performed in Australia as per MSM-PRG-09. It would also help foster and mature the local Australian industry as it transitions to SmallSat class satellites.

7.2 Assembly, Integration and Testing (AIT)

7.2.1 Description

Assembly, Integration, and Testing (AIT) activities ensure each component, subsystem, and final integrated spacecraft is properly prepared and verified to meet the functional and performance specifications. This is better shown in the Systems Engineering 'V', as shown in Figure 26, where AIT activities form the bulk of the second half of the 'V'. As a result, AIT activities are strongly process driven and require good management and reporting.

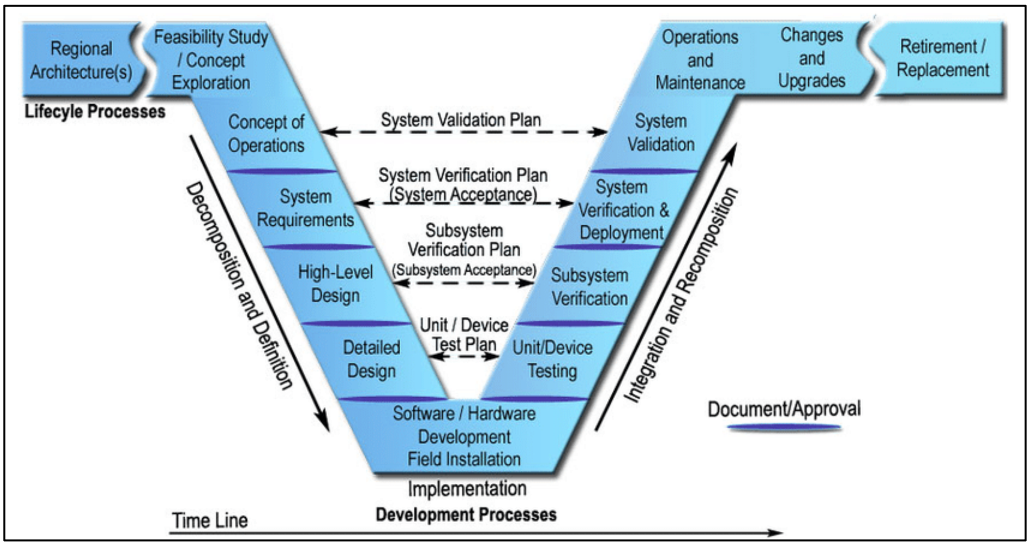


Figure 26: System Engineering 'V' (source: NASA Systems Engineering Handbook).

A high-level description of the AIT activities is presented below:

Preparation and Assembly

The preparation and assembly of the MSM-PF spacecraft and associated support hardware requires a standard laboratory and a 'clean' room facility, with the degree of cleanliness required being dependent on the equipment on the spacecraft (e.g., Optical sensors require greater contamination control). Appropriate practises (e.g., component cleaning, wearing proper protective clothing and electrostatic discharge straps, etc.) must be implemented to ensure the spacecraft is not contaminated or damaged during assembly.

Component and Subsystem Verification

Each component and subsystem must be verified that it performs its required function(s) before progressing to integration with other components & subsystems. Verification activities can range from testing, analysis, and simulation and are dependent on the component/subsystem, the complexity of verifying its function, and how critical the component/subsystem is to the functionality of the entire space system (which includes the instrument(s), spacecraft platform, ground station, and mission operations equipment). Verification activities have a wide range of methods and should be defined for each major component and subsystem during the program.

Payload-specific activities are covered in the next section.

Integrated System Testing & Verification

As an integrated system, which includes the instrument, spacecraft platform, ground station, and mission operations centre, the system must undergo tests and rehearsals to verify that all subsystems function properly together. The exact tests and rehearsals will be specific to the system's architecture and must be defined during the program.

Launch Acceptance Tests

Before accepting the spacecraft for launch, the spacecraft must meet several requirements set out by the launch service provider. Many of these requirements must be verified via tests. These include:

- (Quasi-)Static acceleration tests
- Random vibration tests
- Acoustic tests
- Shock tests
- Bake-out (of spacecraft)
- Gravimetrics
- Electromagnetic Interference (EMI) and Electromagnetic Compatibility (EMC) tests

7.2.2 Implementation options

For AIT and from an Australian capability aspect, a non-exhaustive summary of current capabilities relevant to the MSM-PF is provided below regarding Shock, Vibration, Thermal Vacuum, EMI/EMC, and Radiation.

Note that the following relates to common test requirements for all satellite/payload programs and does not cover dedicated and specific instrument requirements which require specific performance testing and certification facilities/hardware. Those aspects are covered in section 7.3.

The following test facilities relevant to the MSM-PF mission have been identified within Australia:

Australian National University (ANU) National Space Test Facility (NSTF)[44]

- Thermal / Vacuum – Nominal test item envelope 1.55 m x 1.6 m x 1.6 m. The maximum test item mass is 500 kg.
- Shock / Vibration – Maximum random force 22.2 kN Root Mean Square (RMS), maximum test item mass 500 kg.
- EMI / EMC – Internal dimensions 3.7 m x 2.7 m x 2.3 m.
- Radiation – 'Spot Size' beam delivery of 40 mm in diameter which can be rastered over an area of 70 x 70 mm. The target stage can accommodate test boards with maximum dimensions of 250 x 200 mm. The test board can be translated into 'x' and 'y' such that the 'scannable' area of the board is 220 x 200 mm.

Defence Science and Technology Group (DSTG) Eagle Farm

- Thermal / Vacuum – Thermal chamber size 6 m (l) x 3.3 m (w) x 2.56 m (h) with a test item density of 3000 kg/m3. Separate vacuum chamber with an internal diameter of 1.5 m and length of 4.79 m. The maximum weight of the tested article is 900 kg.
- Shock / Vibration – Maximum test item mass 700 kg.
- EMI / EMC – No test capability at this facility.
- Radiation – No test capability at this facility.

The Frontier SI Australian industry readiness assessment [RD-04] also provides an overview of the currently available Australian AIT facilities applicable to the MSM-PF instrument.

7.2.3 Recommended approach for the MSM-PF

A "test as you fly" philosophy is recommended for the Assembly, Integration, and Testing (AIT). The principle of a "test as you fly" approach is that the system must never experience expected operations for the first time in flight. It does not replace other forms of testing, such as Electromagnetic Compatibility (EMC) / Electromagnetic interference (EMI), Shock, Vibration, Thermal / Vacuum, and so on. This approach is important to ensure the following:

- Validation of a system's ability to perform its mission, and not just a verification of system requirements.
- Assessment of mission concepts for testing and calculating the risk for those concepts that are not readily testable.
- A testing process for mission assurance at all levels of assembly, even across interface boundaries.

When it is not possible to "test as you fly", risk management becomes more important. For the MSM-PF, effective "test as you fly" is driven by the mission's concept of operations, flight constraints, flight conditions and mission considerations. To this end, appropriate documentation, hardware, software, trained personnel, etc., is required, and identifying what is feasible and practical to test.

An AIT Plan, a roadmap for all AIT and "test as you fly" activities, must be drawn up early in the development program. The AIT Plan describes the complete AIT process and demonstrates, together with the verification plan, how the requirements are verified by inspection and test. It contains the overall AIT activities and related verification tools (ground support equipment, facilities, etc.), the involved documentation, AIT management and organisation, and the AIT schedule.

The level of detail increases from the early stages of the project to Preliminary Design Review (PDR) and Critical Design Review (CDR). The CDR version is close to the final issue, where only late modifications are implemented. It will be prepared for the different verification levels covering in detail the AIT activities at that level and outlining the necessary lower-level aspects.

The AIT Plan will be a major input to the project schedule and provides a basis for customer review and evaluation of the effectiveness of the AIT program and its proposed elements. It will complement the Verification Plan (a prerequisite to the preparation of the AIT Plan) and considers the test standards defined in the customer requirements.

The AIT programme associated with the MSM-PF mission should:

- Document AIT activities and associated planning.
- Include AIT matrices that link various AIT activities with AIT specifications, procedures, blocks, and hardware models.
- AIT programmes, including inspections to be detailed through dedicated activity sheets.
- The activity sheets will include descriptions of the activity, including the tools and ground support equipment to be used, the expected duration of the activity and the relevant safety or operational constraints. The sequence of activities is best presented as flow charts.

AIT and Engineering should work:

- In an iterative and communicative way, the engineering staff develops AIT specifications (at the equipment and element levels).
- In an iterative and communicative way, the AIT staff turns the AIT specifications into step-by-step AIT procedures.
- A good interaction between engineering and AIT is essential for a good result concerning test contents and sequence of tests.

Post AIT Plan and AIT Procedural development:

- TRR (Test Readiness Review) – A run-through of a check list to verify that all preconditions for the execution of the AIT activity/procedure are fulfilled. Open technical issues are resolved before the TRR.
- PTR (Post-Test Review) – The PTR focuses on a quick formal agreement on breaking the test setup to allow AIT to go on with the planned activities. If this agreement is missing, all further AIT activities are stopped. The PTR is scheduled right after test finalization.
- TRB (Test Review Board) – Major stakeholders are the engineering team supported by the AIT team. During this phase, a test report is prepared where any open points, including Non-Compliance Reports (NCR) resulting from test execution, are addressed. The TRB is the final acceptance board for the relevant AIT activity.

7.3 Payload calibration and validation

The Frontier SI Australian industry readiness assessment [RD-04] provides an overview of the currently available Australian AIT facilities applicable to the MSM-PF instrument.

7.3.1 Description

The calibration and validation process for the MSM-PF requires a standard clean room, a thermal vacuum chamber facility, and a vibration test facility. Equipment for this process includes standard commercial RF test equipment, a custom Fourier transform spectrometer apparatus, a custom beam-filling thermal target, and thermal vacuum and vibration test apparatuses. Laboratory tests encompass the certification of microwave sounder ground test equipment.

Pre- and post-launch calibration and validation (Cal/Val) of the instrument is essential for the accuracy of acquired data and for the data to be combined with data from other EO satellites. Cal/Val will be planned and implemented with the instrument development to ensure overall performance requirements are met.

7.3.2 Implementation options

Pre-launch calibration and validation of the satellite sensor can be carried out within clean room facilities without dedicated high-cost items being manufactured for the purpose. All testing and calibration activities related to the satellite sensor head can be carried out using off-the-shelf hardware. A non-exhaustive list of hardware that could be considered specific to the calibration and validation of the microwave sounder instrument is listed in Table 37.

Table 37: List of potential calibration and validation hardware for the MSM-PF instrument.

Part number	Manufacturer	Description
E8257DS05 or (E8257DV05)	Keysight	Millimeter-Wave Source Module, 140 to 220 GHz, -12 dBm (+4 dBm)
E8257DS06 or (E8257DV06)	Keysight	Millimeter-Wave Source Module, 110 to 170 GHz, -6 dBm (+8 dBm)
E8257DS08 or (E8257DV08)	Keysight	Millimeter-Wave Source Module, 90 to 140 GHz, -2 dBm (+9 dBm)
E8257DS10 or (E8257DV10)	Keysight	Millimeter-Wave Source Module, 75 to 110 GHz, +5 dBm (+14 dBm)
E8257DS12 or (E8257DV12)	Keysight	Millimeter-Wave Source Module, 60 to 90 GHz, +6 dBm (+15 dBm)
E8257D	Keysight	Fully synthesized analogue signal generator with high output power, low phase noise and modulation capability
ME7838G	Anritsu	Vector network analyser – 70 kHz to 220 GHz
Various	CI Systems	Blackbody source – Accuracy to 0.007 Deg. K

An alternative option to acquiring calibration and validation hardware is to contract out the calibration and validation of the satellite sensor head at an increased cost to the customer.

7.3.3 Recommended approach for the MSM-PF

The payload expertise available during the study recommends the following sequential approach to the instrument's calibration and validation.

1- Laboratory Tests

Each digital spectrometer is connected to a commercial PC in a clean laboratory environment. Using a microwave analogue signal generator, each digital spectrometer's spectral performance and noise performance are measured to ensure it meets the requirements.

Then, each millimetre-wave front-end is connected to a commercial synthesizer as the local oscillator. A standard commercial millimetre-wave test equipment (such as a millimetre-wave signal source) then measures the response of each front-end to millimetre-wave signals. This test is repeated with the same model synthesizer as will be used in flight to ensure good performance is maintained.

2- Clean Room Integration and Tests

The Fourier-transform spectrometer's (FTS) and beam-filling thermal targets' individual components are cleaned and assembled in a clean environment.

Measurements on each front-end looking at the FTS are conducted using millimetre-wave signal sources and thermal targets. In these first tests, standard commercial RF test equipment (such as power meters and spectrum analysers) is used instead of the digital back-end to measure the noise performance of the front-ends alone.

The front-ends are then integrated with the digital back-ends without the antenna or calibrator system. The assembly's spectral performance is then measured with the FTS, millimetre-wave signal sources, and the noise performance with the beam-filling thermal target.

These tests are repeated after the integration of the antenna and calibrator. The signal from the internal payload calibrator is then compared with the signal from the external thermal target to ensure they agree.

The data system and thermometers are then integrated, thus completing the entire instrument. The key tests described previously are repeated (observing at the FTS, millimetre-wave signal sources, the external thermal target, and the internal calibration target). Note that this is one of two archival measurements of the spectral performance of the instrument.

3- Thermal Vacuum Chamber Tests

The thermal vacuum chamber must support a wide range of external thermal environments and allow the external thermal target to operate inside the thermal vacuum chamber.

The integrated instrument is installed in the thermal vacuum chamber and observes the external thermal target and the internal calibrator over a wide range of external thermal environments. These measurements will be one of two archival measurements of the instrument calibration.

During the thermal vacuum test, all thermometers' readings in the instrument are recorded to ensure that the system does not overheat or freeze when exposed to a wide range of external thermal environments.

4- Vibration tests

The instrument is installed on a vibration test system, and vibration tests are conducted.

5- Return to the Clean Room Environment

The spectral response measurements with the FTS and millimetre-wave signal sources are repeated to ensure that the exposure to launch-like vibration does not affect the spectral performance. This is the second of the two archival measurements of the spectral response.

6- Return to the Thermal Vacuum Chamber

Observations of the external thermal target and internal calibrator are repeated in various external thermal environments. This is the second of two archival measurements of the calibration. After successfully completing all the above tests and calibration, the instrument can be shipped for integration onto the payload.

7.4 Launch services

7.4.1 Description

Launch services comprise all the services needed to deliver a satellite into orbit. These services primarily consist of the following:

- Launch vehicles,
- Launch site/range, including:
  - Range control,
  - Launch vehicle support facilities such as an erector, pad, propellant storage and filling equipment, tracking stations, communications,
  - Satellite preparation and integration facilities.

Figure 27: Rocket Lab Launch Complex 1, Mahia Peninsula, New Zealand.

Launch services typically consist of two options: dedicated launch and rideshare launch.

Dedicated Launch Service

A dedicated launch is where a customer purchases the entire launch and thus can dictate the launch date (and time) and insertion orbit (within launcher capability). This option has the greatest mission flexibility but is typically more expensive than a rideshare option.

For a 170 kg spacecraft such as the MSM-PF, dedicated launch services from RocketLab or Virgin Orbit are currently the most suitable dedicated launch options, ranging between USD7.5M and USD12M per launch, respectively.

Rideshare Launch Service

For a rideshare launch, a customer purchases an available capacity on a vehicle with a predefined launch date and insertion orbit. The launch date and orbit are determined by the launch service provider or the ‘prime’ customer: the organisation that has purchased most of the launch. This option gives limited mission flexibility but is much less expensive than a dedicated launch. For a 170 kg spacecraft, SpaceX’s rideshare program has the most competitive pricing with a cost of USD1.1M.

Ridesharing does impose slightly greater risk to the mission, as issues such as launch readiness, contamination, structural failure, etc., occurring from other ridesharing spacecraft can impact the spacecraft. To mitigate this, launch service providers have strict “do no harm” requirements to prevent issues from one spacecraft affecting another, but these cannot be completely omitted.

Additionally, because the insertion orbit from the rideshare launch will not likely be the desired final orbit for the spacecraft, the spacecraft will need to propel itself to its final orbit. This will require larger propellant tanks for the extra delta-V manoeuvres. Last-mile-ride services – whose service involves delivering ridesharing spacecraft to their final orbit - are not considered here as this service would increase programmatic efforts and risks beyond that of adding a certain amount of propellant to the spacecraft.

7.4.2 Implementation options

Typically, a Launch Service Provider (LSP) is selected toward the beginning of the programme (usually no later than the start of Phase B of the programme), so the spacecraft can be designed to suit the selected launch vehicle, and the necessary ground support equipment is designed to suit the launch site facilities and launch vehicle.

The LSP should be selected on a range of attributes, with preference given to the combination of attributes that provide the lowest risk. These attributes include:

- Launch vehicle performance:
  - Achievable insertion orbit
  - Mass to insertion orbit
- Cost
- Ability to re-schedule the launch (should the project be delayed)
- Launch success history
- Launch environment:
  - Acceleration
  - Shock
  - Acoustics
- Launch site and facilities
- Geopolitical factors with launch country

Table 38 presents a non-comprehensive survey of currently available launch service providers that apply to the MSM-PF mission. Note that the first three rows present launch capability being developed in Australia that has not yet demonstrated the launch of payloads to orbit at the time of writing.

The Frontier SI Australian industry readiness assessment [RD-04] provides an overview of the launch services currently developing in Australia.

Table 38: Launch service providers applicable to the MSM-PF.

Organisation	Country	Launch vehicle	Launch site	Available orbit inclinations	Launch mass	Cost	*Status*
Equatorial Launch Australia	Australia		Arnhem Space Centre, Northern Territory, Australia				*Under development*
Gilmour Space [1]	Australia	Eris	Bowen, Queensland, Australia		LEO: max. 305kg		*Under development, first launch is scheduled for early 2023 [1]*
Southern Launch	Australia		Whalers Way, South Australia, Australia	Sun-synchronous & polar			*Under development*
Arianespace [2, 3, 4]	France	Vega	Spaceport, French Guiana		SSO (700km): max. 1500kg		*Operational*
		Vega C			SSO (700km): max. 2300kg		
FireFly Aerospace [5, 6]	USA	Alpha	Cape Canaveral, Florida, USA Wallops, Virginia, USA Vandenburg, California, USA	39 – 57 deg. 38 – 75 deg. 58 – 144 deg.	SSO (500km): max. 745kg LEO (200km): max. 1170kg	~USD15M (dedicated launch)	*Initial operations*
Rocket Lab [7, 8]	USA (with NZ subsidiary)	Electron	Mahia Peninsula, NZ *Wallops, Virginia, USA (soon)*	30 degrees to sun-synchronous 38 – 60 deg.	SSO (500km): max. 200kg LEO (500 km, 40°): max. 265 kg	~USD7.5M (dedicated launch)	*Operational*

Organisation	Country	Launch vehicle	Launch site	Available orbit inclinations	Launch mass	Cost	*Status*
SpaceX [9, 10]	USA	Falcon 9	Cape Canaveral, Florida, USA Meritt Island, Florida, USA Vandenburg, California, USA		SSO (500 - 600km): 50kg* SSO (500 - 600km): max. 831kg *USD5500 for each extra 1kg	min. USD275k (rideshare) USD4.99M (rideshare)	*Operational*
Virgin Orbit [11, 12]	USA	LauncherOne	Mojave, California, USA Cornwall, UK	Any	SSO (500km): max. 300kg LEO (230km): max. 500kg	~USD12M (dedicated launch)	*Operational*
EXO Launch	Germany	Various. Coordinates payload launch services with launch service providers; mostly for rideshare missions.					*Operational*
ISILaunch	The Netherlands						*Operational*
Spaceflight [13]	USA				LEO: min. 5kg (3U) LEO: 200kg GTO; 200kg	USD145k USD1.35M USD11.2M	*Operational*

References – *All links are valid as of 27/02/2023*

[1]. https://en.wikipedia.org/wiki/Gilmour_Space_Technologies

[2]. https://www.arianespace.com/wp-content/uploads/2020/06/Arianespace_Brochure_Vega_Sept2019.pdf

[3]. https://www.arianespace.com/wp-content/uploads/2020/06/Arianespace_Brochure_VegaC_Sept2019.pdf

[4]. https://www.arianespace.com/wp-content/uploads/2020/10/SSMS-Vega-C-UsersManual-Issue-1-Rev0-Sept2020.pdf

[5]. https://firefly.com/wp-content/uploads/2022/05/Alpha-PUG-3.1.pdf

[6]. https://en.wikipedia.org/wiki/Firefly_Aerospace

[7]. https://www.rocketlabusa.com/assets/Uploads/Payload-User-Guide-LAUNCH-V6.6.pdf

[8]. https://en.wikipedia.org/wiki/Rocket_Lab

[9]. https://storage.googleapis.com/rideshare-static/Rideshare_Payload_Users_Guide.pdf

[10]. https://www.spacex.com/rideshare/

[11]. https://virginorbitnew.wpenginepowered.com/wp-content/uploads/2020/09/LauncherOne-Service-Guide-August-2020.pdf

[12]. https://en.wikipedia.org/wiki/Virgin_Orbit

[13]. https://spaceflight.com/

7.4.3 Recommended approach for the MSM-PF

In considering MSM-PF desired orbit and mass and considering minimum cost and risks are preferred, the following three launch service options are recommended for MSM-PF:

1. Rocket Lab USA, for dedicated launch,
2. SpaceX, for rideshare launch, or
3. An Australia LSP.

The recommended option for the MSM-PF is a dedicated launch onboard a Rocket Lab Electron[*] launch vehicle. Despite costing approximately USD7.5M, the dedicated launch allows for a more tailored launch service regarding the launch date and insertion orbit. Rocket Lab is preferred over other dedicated launch vehicle options as it has the lowest price, the largest flight heritage, and its primary launch site in Mahia (New Zealand), being close to Australia, makes logistics easier. Additionally, communications back to Australia during spacecraft integration are easier as time-zones are only 2 hours apart.

If a lower-cost launch option is preferred, SpaceX's rideshare program is likely the best choice as it offers the lowest cost per kilogram to orbit, offers a frequent launch schedule – allowing for schedule flexibility, and has shown great reliability. The trade-off is the limited range of insertion orbits, which will result in either a greater spacecraft propellant quantity or the use of an orbital transfer vehicle (OTV) to insert the spacecraft into the desired final orbit. If this option is considered, a detailed analysis of the proposed SpaceX rideshare launches (known as Transporter Missions) will be required to determine the feasibility of a spacecraft obtaining a final SSO with a 05:30 LTAN.

Considering previous Transporter missions, all have been SSO, but none have been close to having a 05:30 LTAN, the closest being 03:10 LTAN[45]. Since LTAN changes whilst in orbit can result in significant delta-V requirements, the additional requirements of the spacecraft's propulsion system and/or the use of an OTV will need to be traded against this launch option's low cost. Based on the MSM-PF spacecraft's projected mass, the expected cost for a SpaceX rideshare launch is approximately USD1.1M[†].

Should an Australian LSP be preferred to maximise Australian involvement, it would need to demonstrate an operational capability before the beginning of Phase B of the MSM-PF program so that the spacecraft can be designed to suit the launch vehicle. However, because it is uncertain whether an Australian LSP can reach operational capability by that milestone, using an Australian LSP is the least likely option at the time of writing.

7.5 Operations

For the puspose of this study, the Bureau has proposed that this mission be operated through a commercial operations service provider. The Frontier SI Australian industry readiness assessment [RD-04] provides an overview of the commercial operations services currently available in Australia.

[*] UNSW Canberra Space does not have any affiliation with the Rocket Lab company. It is recommended here as UNSW Canberra Space's best current assessment.
[†] See https://www.spacex.com/rideshare/ for SpaceX's rideshare launch cost calculator.

7.6 Data Processing and Archiving System (DPAS)

The DPAS has not been considered extensively in this study. The Frontier SI Australian industry readiness assessment [RD-04] provides an overview of the commercial data processing and storage services currently available in Australia.

Data correction and processing algorithms are yet to be defined, as well as archiving requirements (number of copies of each data product). It has, however, been stated during the study that a commercial DPAS solution is desired. Several providers exist, such as Amazon Web Services (AWS), Microsoft Azure and Capricorn Space (an Australian company).

Because the pricing was readily available[*] and it has servers located in Australia (MSM-PRG-02), an AWS-based solution for data storage only was costed. Based on the data volumes presented in section 6.1.1, this solution yielded a total over the mission life of approximately 13,000 USD for storing compressed data and 22,000 USD for storing uncompressed data[†]. Data archiving beyond the spacecraft's decommissioning was not considered in this calculation.

7.7 Spectrum management

Commercially available radios will generally be designed to be operable within the International Telecommunication Union Radio Regulations (ITU RR) constraints.

To operate it, the satellite system must undergo international frequency coordination per the ITU RR, including submitting relevant technical details to the ITU[46]. For an Australian satellite network, this process would involve the Australian Communications and Media Authority (ACMA), which would deal with the ITU on the operator's behalf. The ACMA would also require ground stations in Australia to be licenced.

As the RF spectrum is a finite resource, there is a risk that the approvals required for a particular design may not be obtainable, which may necessitate design changes. The process may also require a significant time to be completed. There are costs involved, consisting of the following:

- labour costs (internal or equivalent outsourced services) associated with preparing information for and corresponding with the ACMA and with coordinating with other relevant spectrum users
- licencing and service fees charged directly by the ACMA
- fees charged by the ITU

In general, the risk, schedule, and cost associated with the process will vary based on several factors, including with:

- the complexity of the request
- the parameters associated with the request
- the number and nature of other authorised spectrum users at potential risk of RF interference
- which specific regulations and procedures apply to the frequency band of interest
- any forthcoming changes in regulation at national or international levels

[*] 0.023 USD/GB/month. Price as of 24/02/2023. https://aws.amazon.com/s3/pricing/
[†] The calculation took into account the storage of a single copy of the raw sensor data accumulated each month.

A LEO mission such as the MSM-PF may require the full-time services of an engineer (or equivalent outsourced services). These labour costs are expected to represent the majority of the costs for spectrum access. However, actual costs are undetermined at this stage and should be the subject of future work. Consulting the ACMA or other subject matter experts about these matters well in advance is highly recommended.

7.8 Mission risk classification

This section presents some generic information on NASA's mission risk classification for reference.

The NASA Procedural Requirements (NPR) framework has defined a four-classification level corresponding to the acceptable risk and project success uncertainty for the development of NASA spacecraft[47]. Table 39 gives an overview of the NASA mission risk classification.

Table 39: NASA mission risk classification[47].

Classification	CLASS A	CLASS B	CLASS C	CLASS D
Priority	Very high	High	Medium	Low
Complexity	Very high	High	Medium	Medium to Low
Lifecycle cost	High	Medium to High	Medium	Medium to Low
Mission life (years)	> 5	5 > - > 3	3 > - > 1	< 1

Risk classifications have programmatic and technical implications at all mission levels, including in mission management detail, project structure, systems engineering, quality assurance, testing and verification. The NPR provides the level of mission assurance that must be implemented and provides guidance in using applicable standards and approaches to ensure project success. Elements of each assurance domain (e.g., environmental testing, materials, software), as defined across the risk classifications, can be applied as needed to meet the intent of the specific classification applied to a project[48]. All aspects of the missions are adjusted to ensure an appropriate mission risk management strategy is developed and properly implemented.

This study has not fully considered elements relating to the proposed mission's availability, reliability, and redundancy. However, it is possible that the proposed mission would fall in Class C for the MSM-PF and Class B for the MSM constellation.

The development cost differs between two comparable performance Class-B and Class-C missions. The Class-C mission is expected to cost less than the Class-B mission, given the different risk tolerance and complexity levels of each mission. A cost analysis of NASA Class A through D optical remote sensing payloads showed that the median cost per kg for a Class A/B payload was over USD1M/kg while the median cost for a Class C/D instrument was about USD0.5M/kg[49]. Another study of the Johns Hopkins University Applied Physics Lab missions showed a strong correlation between mission/payload hardware complexity and risk tolerance with the cost for program management, systems engineering and mission assurance functions[50].

Common risk mitigation avenues include:

- Use of high TRL components and flight-proven technologies.
- Procurement through established suppliers with flight heritage and compliant with relevant quality standards.
- Implementation of redundancy for critical systems.

The risk classification also has implications on the ground segment. A level of redundancy can be built into the ground station network and data processing and archiving system to ensure the continuity of operations.

A consistent risk management approach and a detailed risk assessment should be developed in future work to identify and mitigate major risks and impacts early in the program.

8 Mission Costing & Schedule

All costs are in Australian Dollars, except where explicitly mentioned.

8.1 Proposed schedule

The proposed schedule for this mission is presented in Table 40. The mission is expected to run for 8.5 years, with in-orbit commissioning completed within 5 years of project kick-off (as per requirement MSM-PRG-10), 3 years of operations, and 6 months allocated to decommissioning, deorbiting, and project wrap-up. This schedule was developed based on NASA's project lifecycle phases[1].

The first 5 years are allocated for activities to develop and commission the spacecraft in preparation for operation. The content of each phase is briefly discussed below:

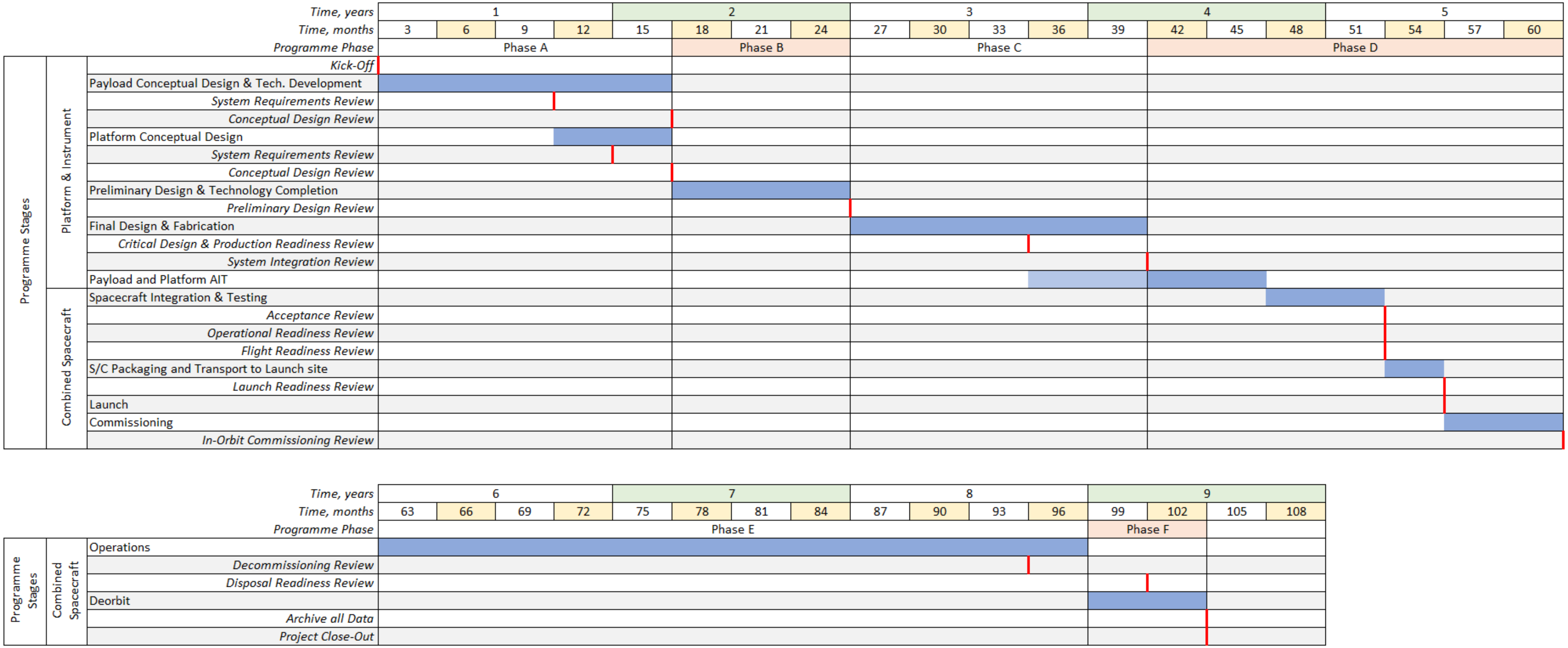
- 15 months for Phase A / conceptual mission design work. This period is weighed longer than typical mission programmes as it is thought necessary to allocate more time for instrument technology development to mature the digital spectrometer technologies proposed. In comparison, the platform conceptual design phase has only been allocated 6 months as no new technologies are being considered. Before the completion of Phase A, the System Requirement Reviews must be completed to ensure all system requirements are adequately captured. Phase A is completed after Conceptual Design Reviews for both the instrument and platform have been passed.
- 9 months for Phase B / preliminary design work. From this phase onwards, the instrument and platform should be developed in parallel to ensure that all the systems' interfaces remain compatible. Some early manufacturing and testing may be carried out to de-risk the development of certain mission components and/or systems. Phase B is completed after a Preliminary Design Review for the entire mission has been passed. Long lead items might be purchased during this period.
- 15 months for Phase C / final design and fabrication work. The bulk of the detailed design work has been allocated 9 months to completion, at which point a Critical Design & Production Readiness Review should be conducted. After this review, the bulk of manufacturing will likely be undertaken. The purchase of the remaining items and the receipt of all items, should be completed during this phase. Flight qualification testing of the platform and instrument should be conducted during this phase. Some other initial integration and testing work will likely be started to de-risk any high-risk aspects of the mission. Phase C is completed with a System Integration Review.
- 21 months of Phase D / AIT, launch preparation, launch, and commissioning work. 6 months have been allocated to complete the assembly, integration, and testing (AIT) of the instrument and platform, with a further 6 months allocated to the integration between the instrument and platform. This 12-month period will include Flight Acceptance testing and Acceptance Review, as well as full system integration tests involving the spacecraft, ground station, and mission operations which will be finalised following an Operational Readiness Review and a Flight Readiness Review to ensure everything is ready to launch and commission the spacecraft in orbit. Following this, 3 months have been allocated to prepare and transport the spacecraft to the launch site, perform launch vehicle integration activities, conduct a launch readiness review, and launch the spacecraft.

After the spacecraft has arrived in-orbit, 6 months have been allocated to commission the platform (initially) and then the instrument. This phase is completed once an In-Orbit Commissioning Review has been completed to ensure the spacecraft, ground stations, mission control centre, and operators are ready to operate the spacecraft.

Following the development phases, Phase E begins, where operations proceed for 3 years. A few months before the end of this phase, a Decommissioning Review should be performed to ensure that the project/operations will not be extended.

Phase F begins when operations have been terminated, the spacecraft is deorbited, and the project is ended. A Disposal Readiness Review should be conducted before deorbiting the spacecraft. This phase, and thus the entire project, is completed once the spacecraft is deorbited, all data is archived, and the project has been closed out.

Table 40: Proposed MSM-PF mission schedule.



8.2 Estimated mission cost

The mission cost was broken down into the following main components:

Combined System Costs

System-level costs incorporated the costs associated with mission-level project management and administration and the Assembly, Integration, and Testing (AIT) of the completed spacecraft, Ground Support Equipment (GSE), launch, and regulatory costs.

Payload Costs

Instrument costs were broken down into sub-sections consisting of:

- Labour, including management, engineering, and technical personnel.
- Components & materials,
- AIT activities, including specialised equipment and facility hire.

Each of these sub-sections was then further refined to levels where sufficient confidence could be given to each line-item.

Platform Costs

Two platform options were costed: a bespoke platform custom designed & manufactured specifically for the mission, and a COTS integrated bus.

The bespoke platform, like the payload costs, were broken down into sub-sections consisting of:

- Labour, including management, engineering, and technical personnel.
- Components & materials,
- AIT activities, including specialised equipment and facility hire.

The cost was estimated by budgeting for a specialised team of Australian engineers designing a custom spacecraft assembled primarily from COTS components. Furthermore, all AIT activities were costed using local costs as they would be mostly undertaken in Australia (as per MSM-PRG-09). The bespoke platform cost breakdown resulted in a higher cost than a COTS platform as the non-recurring engineering (NRE) effort is significantly higher (because of the custom build), custom ground support equipment (GSE) costs need to be included, and a number of system spares were budgeted for but are unlikely to be re-purposed if not used.

The COTS platform was costed by requesting Rough-Order-of-Magnitude (ROM) costs from industry. Unfortunately, within time allotted in preparing this report, only one international supplier could provide a ROM cost estimate. The cost estimate provided included NRE, spacecraft, and FlatSat hardware. It must be noted that actual project costs can range between -25% to +75% of the ROM cost.

Launch Costs

Launch costs include all associated costs, including the launch, costs for four persons to the launch site (calculated for New Zealand, assuming the Rocket Lab Electron launcher) to assist with integrating the spacecraft to the launch vehicle, and packaging and freight of spacecraft to the launch site.

A rideshare launch will cost significantly less than a dedicated launch (about USD1.1M for a SpaceX Transporter launch) but will likely incur additional costs and risks on the platform. Those impacts have not been investigated in this study and may be the subject of future work.

Operating Costs

Operating costs cover personnel and commercial ground station costs for the on-orbit duration of the mission, as well as the storage costs of the data. It does <u>not</u> include data processing costs, as the processing requirements are unknown at this stage.

The cost breakdown is shown below in Table 41, with more detailed costs presented in Appendix C.

Table 41: Overall MSM-PF mission cost breakdown.

Mission Component	Bespoke platform implementation ($M)	COTS platform implementation ($M)	Notes
Combined system costs	4.4	4.4	
Instrument costs	10.7	10.7	
Platform costs	15.9	3.6	
Launch costs	11.2	11.2	Baseline dedicated launch vehicle: Rocket Lab Electron.
Operational costs	4.5	4.5	Includes 6 months commissioning and 3 years of operations.
Sub-total	**46.7**	**34.3**	
Overall uncertainty margin (10%)	4.7	3.4	
Overheads (35%)	7.1	4.6	Only applied to labour costs.
Sub-total	**58.5**	**42.3**	
Net margin (10%)	5.8	4.2	Margin dependent on contracted organisation.
Total mission cost	**64.3**	**46.5**	

<u>The MSM-PF mission proposed and costed here has a very capable instrument that meets most objective mission requirements. The mission requirements could still be met with an instrument with a lower specification that would significantly reduce cost.</u>

8.3 Costing methodology

The costing methodology involved breaking down the expected costs for each mission element to a level of detail where line items could be costed to the highest confidence possible.

Uncertainty margins were applied to all line items, and the percentile was dependent on the confidence of the cost estimate. Typical margins ranged from 5% for costs with high confidence (i.e., COTS prices) to 50% for costs with lower confidence.

8.3.1 General costing factors

The following are general factors taken when estimating the costs of the MSM-PF mission.

- All costs considered are taken as those for FY22. No projections have been made to estimate costs for future dates.
- All costs are in Australian Dollars unless explicitly mentioned.
- Currency exchange rates were calculated from a 5-year average between June 2017 to June 2022 based on exchange rates listed by the ATO[51]. Rates were calculated as follows:
    - USD to AUD: 1.343
    - EUR to AUD: 1.547

8.3.2 Labour Rates

Individual labour rates were estimated for the following professions deemed necessary to support the mission development and operation:

- Project manager
- Engineer (various roles)
- Technicians
- Administrator

A 35% on-cost was applied to the baseline salary rates to account for the following additional costs per person:

- Superannuation
- Payroll tax
- Workers’ compensation
- Provision for long service leave
- Leave loading

This 35% rate was based on mission and project experience acquired at UNSW Canberra Space.

The labour rates used in this costing are shown in Table 42 below.

Table 42: Labour rates.

Role	Base Salary Costs (AUD)	On-Cost (%)	FTE incl. On-Costs (AUD)	Ref.
Project Manager	$ 125,000.00	35%	$ 168,750.00	1
Engineer	$ 115,000.00	35%	$ 155,250.00	2
Technician	$ 72,000.00	35%	$ 97,200.00	3
Administrator	$ 80,000.00	35%	$ 108,000.00	4

References – *All links are valid as of 27/02/2023*

1. https://info.aipm.com.au/hubfs/Reports%20and%20major%20content%20assets/2021%20AIPM%20Salary%20Report.pdf
2. https://members.professionalsaustralia.org.au/documents/Engineers/RemunerationReport/Professional-Engineers-Employment-and-Remuneration-Survey-Report-2020-21.pdf
3. https://au.talent.com/salary?job=technician
4. https://au.talent.com/salary?job=administrator

8.3.3 Overheads

A 35% overhead (currently an estimate) was applied to all labour costs to account for business operating expenses for the mission. Such business operating expenses include but are not limited to:

- Building costs (rent, depreciation, etc.),
- Maintenance,
- Utilities
- Insurance,
- Ancillary staff, such as board, legal, administration, human resources, etc.

8.3.4 Other

An overall uncertainty margin of 10% was applied to all expenses, including labour, hardware, and services, to account for costing uncertainty/error.

An additional net margin of 10% was applied to all sub-totalled costs (addition of labour, hardware, services, overheads, overall uncertainty margin) to account for the profit a prime contractor may wish to receive for undertaking the project.

8.4 Caveats and limitations

The method used in this study presents some limitations that are listed below:

- Several line-item costs were best estimates rather than quoted items. Most manufacturers require some level of mission funding confidence to provide quotes, as these usually require some engineering work to be determined. Should any of the costs in this report require justification, these can be made available on request.
- This costing is based on the schedule proposed in section 8.1. A different mission schedule will lead to a different mission cost due to the difference in labour costs.
- The COTS platform costing is based on a single industry data point, and other suppliers may provide a very different quote.

9 Recommendations and Open Points

This section identifies and provides recommendations for future work and open points that were out of the scope of this Pre-Phase A study. Most of these items will likely need to be addressed to further develop the proposed MSM-PF concept. These recommendations are categorized in work packages for clarity.

Program- and mission-level

- Exploration of the technical feasibility of the development of an Australian digital spectrometer coupled with the remaining SSMIS instrument and assessment of the likely impacts on cost and schedule of the MSM pathfinder as well as pros and cons of pursuing this option relative to developing the entire science payload and launching on a small satellite in SSO.
- Assessment of the scope, benefits, cost, and schedule of a CubeSat pathfinder and/or a ground demonstrator in view of deploying an operational MSM constellation.
- Exploration of user segment implementation options, with a particular focus on algorithm development, user training and science team formation.
- Definition of the MSM-PF and MSM missions risk classification or tolerance and identify or develop appropriate procedures to manage risk.
- Trade-off between various MSM constellation configurations and explore and examine procurement scenarios (how many spacecraft to build per year and when to launch them) once the constellation configuration is finalised.
- Engagement with international research teams to gather expertise and pave the way for future collaboration.

System-level

- Extensive survey of suitable commercial platform options for the MSM-PF spacecraft and engagement with manufacturers.
- Trade-off between sourcing a commercial platform a building a bespoke platform.
- Refinement of the concept of operations.
- System-level risk assessment to identify and mitigate critical risks.
- Trade-off of applicable launch options (rideshare vs dedicated) in more detail.
- Start manufacturer/component selection and baselining as appropriate.
- Start working on subsystem-level interfaces as appropriate.

Orbit

- Determination of station-keeping tolerances (orbital tube).
- Exploration and trade-off study of various orbit options and finalisation of baseline orbit.

Payload

- Technological survey to determine existing capability and design feasibility.
- Mechanical and thermal design of the payload (including thermal stability requirements).
- Refinement of cost, mass, data rate and volume estimates for objective, breakthrough and threshold instruments configurations.
- Refinement of onboard calibration requirements.
- RFI analyses to determine the impact of downlinking operations on payload data quality.
- Discussion on polarization and calibration requirements (not discussed in detail in this study).
- Analysis and trade-off study of architecture options to determine whether a 75-cm antenna can be accommodated to achieve a 5 km ground resolution.
- Discussion and optimisation of instrument scanning pattern.

Communications subsystem

- Refinement of uplink and downlink data volume estimates (payload and TT&C).
- Refinement of downlink link budget.
- Design of TT&C link.
- Final selection of commercial ground station network and engagement with providers.
- Obtain cost, schedule, and risk estimates associated with RF spectrum access and update communications subsystem designs as needed.

Electrical power system

- Refinement of the power budget by confirming reference component selection.
- As the concept of operations of the MSM-PF spacecraft is developed, refinement of power budgets for more operational modes by including off-nominal operational modes.
- Optimisation of the solar array deployment angles.

Attitude determination and control subsystem

- Determination of magnetorquers specifications based on reaction wheels specifications, spacecraft mass distribution and disturbance torques.
- Determination of ADCS computer requirements.
- Determination of the impact of the payload’s moving parts (rotator) on spacecraft stability and vibrations.

Propulsion subsystem

- Further investigation of the applicability of an electric propulsion subsystem.
- Re-entry risk and casualty assessment.
- In-orbit collision risk assessment.
- Investigation of propellant sloshing and pointing considerations.

- Further refinement of the delta-V budget.

Structure and thermal subsystem

- Refinement of the volume and form factor estimates.
- Design of the spacecraft configuration, structure and separation system interface.
- Further refinement of the mass budget.
- Determination of environmental constraints during launch (after selecting a launch vehicle).
- Start a more detailed thermal design of the spacecraft after actual components are selected.

Onboard data handling subsystem

- Determination of onboard storage and access requirements.
- Determination of re-programmability requirements.
- Determination of data transformation and throughput needs.
- Determination of encryption and security requirements.
- Assessment of compression requirements and applicable compression algorithms.

Ground segment

- Determination of data processing and archiving requirements and archive locations.

Appendix A Preliminary Payload Downlink Design Analysis

Table 43 shows link specifications for the preliminary payload downlink subsystem design. Calculations were made to represent the worst case in performance of the link within its minimum elevation specification, noting that the use of an isoflux antenna limits the variation in the link margin compared to other fixed-antenna designs.

Table 43: MSM-PF payload downlink subsystem—link specifications.

Parameter	Value	Unit	Comment
Frequency band	8025 – 8400	MHz	The ITU-RR allocates the earth exploration–satellite (space-to-Earth) service to this band. Supported by many commercially available radios.
Spacecraft radio output power	2	W	Common upper value for commercially available like systems [52].
Spacecraft boresight antenna gain	-1	dBi	Value of commercially available example[26]. Increases away from boresight up to the maximum at approximately 60° off boresight.
Symbol rate	30	Mbaud	Reasonable, commercially available value.
Acceptable bit error rate (approximate)	10^{-7}	bits/bit	See section 6.1.1.
Ground station antenna gain	50.5	dBi	Nominal 5.4 m dish value for 55% efficiency at 8 GHz
Minimum elevation	20	°	Losses increase significantly at lower elevations. 20 deg results from a trade-off between access time and performance requirements.
Ground station equivalent noise temperature	500	K	Conservative number.
Modulation	QPSK	-	
Coding rate	2/5	bits/bit	
Filtering	SRRC(0.35)	-	
User data rate	23.7	Mbps	Calculated.
Spectral occupied bandwidth	35.1	MHz	Calculated.
Link margin (nominal)	3.1	dB	Calculated.

Appendix B Additional payload considerations

Thermal considerations

To ensure data quality and reliability, microwave sounders have thermal stability requirements. At this conceptual design stage, payload thermal requirements have not been derived. However, this aspect of the payload design has been briefly discussed during the study and is captured here.

- The calibration load will likely require several thermometers and heaters to stabilise its temperature, as it needs to be a stable reference. The order of magnitude of this requirement is to keep the calibration load at ±10 mK over 1 minute. MWS thermal requirements for the calibration load can be found here[53].
- The analogue millimetre-wave parts of the front-end also require to be thermally stable. The order of magnitude of this requirement is to keep the analogue front-end parts at ±50 mK over 10 minutes.
- The RF and digital electronics of the back-end need to be kept within their operating temperature range with less stringent thermal stability requirements. An order of magnitude of this requirement is to keep the back-end electronics at ±500 mK over 10 minutes.
- It is expected that these parts have a large thermal inertia due to their masses and would therefore be naturally stable in temperature. Long-term drifts can and should be prevented using coolers.
- It is recommended (but not necessary) that the payload have its own radiator to evacuate the generated heat to minimise and ease the number and design of interfaces with the platform. This is particularly the case if the platform is sourced as a commercial off-the-shelf element.
- Component characterisation will be required, in particular, the impact of temperature on the measured voltage out of the LNAs and, therefore, on the inferred atmospheric temperature and humidity.

It is expected that thermal design and control will be a significant work package in the payload design and will require dedicated personnel and equipment.

Noise sensitivity analysis

A key requirement for the MSM-PF instrument is that it shall deliver sensitivity per equivalent sensor channel bandwidth that meets or exceeds the state-of-the-art ATMS sensor (MSM-USR-06). Given the different sensor channel bandwidths between ATMS and MSM-PF, this requirement is most naturally quantified as an equivalent system temperature. In Table 44, the noise equivalent temperature difference requirements for each ATMS channel are scaled by each channel bandwidth to yield the equivalent system temperature required at each band for the MSM-PF instrument. These vary from 1,080-6,790 K across 23.8-190 GHz. Surveying commercially available low-noise amplifiers (LNAs) for each of these bands, it is found that the noise requirements can be met at all required frequency bands, with margins varying by a factor of 2.8 to a factor of 12.8. Other than the system temperature, additional noise does often appear in radiometer systems, but continued advancement in the performance of commercial millimetre-wave amplifiers and other components are a key enabling technology for the mission and are expected to retire a wide range of risks.

Table 44: MSM-PF equivalent system temperature requirements.

ATMS Channel	Band centre (GHz)	SSB (1) or DSB (2) Factor*	Bandwidth at detector (GHz)	RF bandwidth (GHz)	Required NEΔT (K)	Equivalent T_{sys} (K)†	Commercial‡ LNA T_{sys} (K)	Ratio
1	23.8	1	0.27	0.27	0.5	1102.3	228	4.8
2	31.4	1	0.18	0.18	0.6	1080.0	292	3.7
3	50.3	1	0.18	0.18	0.7	1260.0	292	4.3
4	51.76	1	0.4	0.4	0.5	1341.6	292	4.6
5	52.8	1	0.4	0.4	0.5	1341.6	292	4.6
6	53.596pm0.115	2	0.17	0.34	0.5	1236.9	292	4.2
7	54.4	1	0.4	0.4	0.5	1341.6	292	4.6
8	54.94	1	0.4	0.4	0.5	1341.6	292	4.6

* Single Sideband (SSB) and Double Sideband (DSB) information have been retrieved from https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2013JD020483. Accessed on 21/02/2023 .
† Assumes an 18 ms sampling. Source: https://www.star.nesdis.noaa.gov/jpss/documents/ATMS_SRF/CM-RELEASE-COPY-RE-20319_RevD_CalibrationDataBook-X.pdf. Accessed on 21/02/2023.
‡ Commercial LNAs used for this analysis are Eravant LNAs and can be found in https://www.eravant.com/products/amplifiers/low-noise-amplifiers. Accessed on 21/02/2023.

ATMS Channel	Band centre (GHz)	SSB (1) or DSB (2) Factor*	Bandwidth at detector (GHz)	RF bandwidth (GHz)	Required NEΔT (K)	Equivalent T_{sys} (K)†	Commercial‡ LNA T_{sys} (K)	Ratio
9	55.5	1	0.33	0.33	0.5	1218.6	292	4.2
10	57.290,334	2	0.155	0.31	0.75	1771.7	292	6.1
11	57.290,334pm0.217	2	0.078	0.156	1	1675.7	292	5.7
12	57.290,344pm0.3,222pm0.048	2	0.036	0.072	1	1138.4	292	3.9
13	57.290,344pm0.3,222pm0.022	2	0.016	0.032	1.5	1138.4	292	3.9
14	57.290,344pm0.3,222pm0.010	2	0.08	0.16	2.2	3733.5	292	12.8
15	57.290,344pm0.3,222pm0.0045	2	0.03	0.06	3.6	3741.2	292	12.8
16	88.2	1	2	2	0.3	1800.0	634	2.8
17	165.5	2	1.15	2.3	0.6	3860.6	1175	3.3
18	183.31p,7.0	2	2	4	0.8	6788.2	1175	5.8
19	183.31pm4.5	2	2	4	0.8	6788.2	1175	5.8
20	183.31pm3.0	2	1	2	0.8	4800.0	1175	4.1
21	183.31pm1.8	2	1	2	0.8	4800.0	1175	4.1
22	183.31pm1.0	2	0.5	1	0.9	3818.4	1175	3.2

Appendix C Itemized Mission Costing

This appendix presents a more detailed breakdown of the assessed mission cost. More information on the various assumptions can be made available on request.

Table 45: Estimated mission cost breakdown utilising a bespoke platform.

Mission Component	Cost ($M)	Cumulative margin (%)	Total cost ($M)
Combined System Costs	**3.94**	**11.7%**	**4.40**
Labour	3.43	10.0%	3.77
Assembly, Integration, & Testing	0.36	20.0%	0.43
Regulatory	0.16	30.0%	0.21
Instrument Costs	**9.38**	**13.6%**	**10.66**
Labour	6.51	10.0%	7.16
Component & Material	2.32	22.4%	2.84
Assembly, Integration, & Testing	0.55	20.0%	0.66
Platform Costs	**13.83**	**15.0%**	**15.90**
Labour	6.70	10.0%	7.37
Component & Material	7.14	9.0%	7.78
Assembly, Integration, & Testing	0.63	20.0%	0.76
Launch Costs	**10.16**	**10.1%**	**11.19**
Operational Costs	**4.13**	**8.6%**	**4.49**
Labour	1.86	10.0%	2.05
Facility & Equipment	1.19	5.0%	1.25
Ground Segment	1.09	20.0%	1.19
Sub Total			**46.65**
Overall Uncertainty Margin (10%)			**4.66**
Overheads (35%)			**7.13**
Sub Total			**58.44**
Net Margin (10%)			**5.84**
Assessed total mission cost			**64.29**

Table 46: Estimated mission cost breakdown utilising a COTS platform.

Mission Component	Cost ($M)	Cumulative margin (%)	Total cost ($M)
Combined System Costs	**3.94**	**11.7%**	**4.40**
Labour	3.43	10.0%	3.77
Assembly, Integration, & Testing	0.36	20.0%	0.43
Regulatory	0.16	30.0%	0.21
Instrument Costs	**9.38**	**13.6%**	**10.66**
Labour	6.51	10.0%	7.16
Component & Material	2.32	22.4%	2.84
Assembly, Integration, & Testing	0.55	20.0%	0.66
Platform Costs	**2.99**	**19.5%**	**3.54**
NRE	0.30	20.0%	0.35
Spacecraft	2.60	20.0%	3.12
FlatSat	0.09	10.0%	0.10
Launch Costs	**10.16**	**10.1%**	**11.19**
Operational Costs	4.13	8.6%	4.49
Labour	1.86	10.0%	2.05
Facility & Equipment	1.19	5.0%	1.25
Ground Segment	1.09	20.0%	1.19
Sub Total			**34.31**
Overall Uncertainty Margin (10%)			**3.43**
Overheads (35%)			**4.55**
Sub Total			**42.29**
Net Margin (10%)			**4.23**
Assessed total mission cost			**46.52**

Appendix D Customer Requirements Cross-Reference Matrix

Req. No.	Description	Cross-Reference
MSM-OBJ-01	To support Bureau of Meteorology numerical weather prediction at regional and global scales with temperature and humidity sounding information at 50-60 GHz and 183 GHz respectively, with radiometric noise not greater than the ATMS instrument.	Section 5.2.1, Section 5.3, Section 5.4, Section 7.3.2.
MSM-OBJ-02	To support Bureau of Meteorology Tropical Cyclone and severe precipitation applications with observations at 89-90 GHz, with radiometric noise not greater than the ATMS instrument.	Section 5.2.1, Section 5.3, Section 5.4, Section 7.3.2.
MSM-OBJ-03	To support next-generation numerical weather prediction with improvements in vertical resolution of the measurements and enhanced mitigation against radio frequency interference (RFI) via provision of higher spectral-resolution information than the MWS instrument in the main frequency ranges of interest.	Section 5.2, Section 5.2.1, Section 5.4.
MSM-OBJ-04	To develop microwave instrumentation that delivers improvements in one or more of the following areas: ▪ Better spatial resolution than the MWS instrument in support of tropical cyclone monitoring and high-resolution numerical weather prediction. ▪ A breakthrough improvement in radiometric performance. ▪ Better Size Weight and Power for Cost (SWaP-C) than microwave sounders currently flying or approaching launch, facilitating the development of a constellation mission in support of rapid-update data assimilation and tropical cyclone monitoring.	Section 3.2.2, Section 5.5, Appendix B.
MSM-OBJ-05	To provide measurements that support detection, monitoring and forecasting of precipitation including one or more of the following: ▪ Contributing to more frequent measurements that allow the detection of hydrometeors and precipitation. ▪ Increased vertical information content for cloud liquid water and water vapour, especially in the boundary layer. ▪ Including frequencies below 50 GHz that allow better characterisation of precipitation.	Section 5.3.
MSM-OBJ-06	To provide measurements at frequencies below 50 GHz that support land, sea and ice-surface applications including windspeed, surface temperature and surface emissivity.	Section 5.3.

Req. No.	Description	Cross-Reference
MSM-OBJ-07	To build international partnerships to facilitate the development of a joint constellation mission, reducing risk, improving collaboration opportunities, and creating international interest in the mission.	Section 3.2.3, Section 7.1.4.
MSM-OBJ-08	To develop an instrument that fits a standard bus, creating opportunities for ride-share and other launch options.	Section 5.5.5, Section 7.1.2, Section 7.1.4.
MSM-OBJ-09	To provide measurements that either: ▪ Fill a gap in the global observing system, enabling Australia to contribute in a meaningful way to core observations under WIGOS ▪ Increase the temporal coverage of standard frequency microwave observations, providing additional sounding data that will benefit global numerical weather prediction and worldwide severe weather monitoring	Section 3.2.1, Section 4.3.2.
MSM-OBJ-10	To provide polar coverage to support the Bureau's Antarctic modelling and climate change research.	Section 4.3.1

Req. No.	Description	Cross-Reference
MSM-PRG-01	The mission shall deliver capability into the Australian space industry.	Section 3.2.3, Section 7.1.4.
MSM-PRG-02	The mission shall store all data from the mission in Australia and make it available from the data hub.	Section 6.1.1, Section 7.6.
MSM-PRG-03	The mission shall consider the possibility of locating the Mission Operations Centre (MOC) and its staff in Australia or sharing the MOC with an international partner.	Section 4.2.3, Section 7.5. *Not addressed in detail in this report.*
MSM-PRG-04	The mission shall adhere to Australian policies and industry best practices in areas including, but not limited to: security, privacy, data policy, interoperability and responsible use of space.	Section 4.3.1, Section 6.1.1, Section 6.4.1, and derived requirement CDF-R-DAT-04.
MSM-PRG-05	The mission data, products and services shall be made freely available.	*Not addressed in detail in this report.*
MSM-PRG-06	The mission shall leverage existing National Space Program and Sub-Program governance, procurement strategy and ground segment wherever viable.	Section 1.3. *Not addressed in detail in this report.*
MSM-PRG-07	The mission budget is $30-60M.	Section 8.2.
MSM-PRG-08	The mission shall align with the Bureau's strategy.	Section 3.
MSM-PRG-09	The mission shall undergo space segment Assembly, Integration and Testing in Australia as far as possible.	Section 7.2.2.
MSM-PRG-10	The pathfinder mission shall complete in-orbit commissioning within 4-5 years of the kick-off of the implementation phase.	Section 8.1.

ID	Parameter	Objective-O	Breakthrough-B	Threshold-T	Notes
MSM-USR-01	Spectral Bands	50-70 GHz, 90 GHz, 183 GHz, Plus: 118 GHz, 150GHz Plus: 31.4 GHz,36-7 GHz, 23.8 GHz, 19 GHz OR: Complete spectral coverage between 19 and 183 GHz	50-60 GHz, 90 GHz, 183 GHz, Plus: 118 GHz, 150 GHz	50-60 GHz, 90 GHz, 183 GHz	A detailed design is yet to be developed, but the instrument sizing and mission design were based on the "Objective" requirements.
MSM-USR-02	Number of channels	Approx. 1800	Approx. 1100	Approx. 400	
MSM-USR-03	Spectral resolution v /Δv	5000 (T) 4575 (WV)	2500 (T) 1830 (WV)	1250 (T) 915 (WV)	
MSM-USR-04	Spatial Coverage	Global	Global	Full coverage of Australia including its surrounding area	The pathfinder's orbit will allow full coverage within a repeat cycle (7 days). See the orbit discussion in section 4.3.
MSM-USR-05	Swath width	>=2200 km (tied to orbit height and viewing geometry)	>=2052 km (tied to orbit height and viewing geometry)	>=1800 km (tied to orbit height and viewing geometry)	The proposed orbit altitude (605.5 km) results in a 1950 km swath width. The operational constellation will likely be higher (~800 km). See the orbit discussion in section 4.3.

ID	Parameter	Objective-O	Breakthrough-B	Threshold-T	Notes
MSM-USR-06	Noise Level (NEΔT)	≤ ATMS actual * 0.5 for spectrum integrated to ATMS SRF and IFOV	≤ ATMS actual * 0.66 for spectrum integrated to ATMS SRF and IFOV	≤ ATMS actual for spectrum integrated to ATMS SRF and IFOV	See Appendix B for more details on achievable noise performance.
MSM-USR-07	Spatial resolution (footprint)	≤5 km at nadir	≤15 km at nadir for temperature sounding. ≤7 km at nadir for humidity.	≤25 km at nadir for temperature sounding. ≤15 km at nadir for humidity.	Assumed a 10 km resolution throughout this study, acknowledging this requires a detailed design of the antenna. This is relevant to the data budget.
MSM-USR-08	Geolocation accuracy	≤10% spatial resolution	≤ 17% spatial resolution	≤25 % spatial resolution	The attitude knowledge system was sized to determine the spacecraft's attitude within 1 km on the ground.
MSM-USR-09	Viewing Geometry	Up to +/-55°, multiple view angles per ground footprint	Up to +/-55°	Up to +/-55°	The objective requirement requires a conical scanner which was ruled out in section 5.2.2.
MSM-USR-10	Polarization	Low-frequency channels (≤37 GHz) polarised	Single linear polarization changing with scan angle (as ATMS)	Single linear polarization changing with scan angle (as ATMS)	Not discussed in detail in this study.
MSM-USR-11	Spatial sampling	Oversampling (Nyquist at minimum)	Contiguous Footprints	Non-contiguous	A conservative sampling frequency of 200 Hz was assumed.

ID	Parameter	Objective-O	Breakthrough-B	Threshold-T	Notes
MSM-USR-12	Calibration mechanism	2-point calibration -40 to -50 dB return loss from onboard source	2-point calibration -40 to -50 dB return loss from onboard source	2-point calibration	Not discussed in detail in this study.
MSM-USR-13	Calibration accuracy	≤0.2 K	≤0.5 K	≤1 K	Not discussed in detail in this study.
MSM-USR-14	Temporal Refresh	Sub-hourly	≤Every 3 hours	≤Every 6 hours *for single pathfinder, once every 12 hours is acceptable*	The temporal resolution requirement can only be met via a constellation.
MSM-USR-15	Instrument lifetime	7 years	5 years	3 years *for a single pathfinder, a 2-year lifetime is acceptable*	Designed for 3 years, as 5 and 7 years will involve a system redundancy and reliability requirement that is likely, not achievable within the mission's cost and schedule constraints.
MSM-USR-16	Global data timeliness	90% within 1 hour	90% within 2 hours	NRT - 90% within 3 hours 30 mins *for single pathfinder, there is no NRT timeliness requirement*	Designed the communications subsystem to a 90% within 20 min data latency requirement for local data and 1 hour for global data as per the Mission Requirements Document [RD-03]. See section 6.1.
MSM-USR-17	Local data timeliness	90% within 10 mins	90 % within 15 mins	90 % within 20 mins	

Appendix E Derived Requirements Summary

ID	Type	Requirement
CDF-R-ORB-01	**Orbit**	The orbit shall facilitate vacation of the LEO-protected region within 25 years after the end of the nominal mission.
CDF-R-ORB-02	**Orbit**	The orbit shall either: ▪ Provide redundant coverage in the early morning, mid-morning and afternoon orbital planes that comprise the core WIGOS LEO component, or ▪ Increase temporal sampling frequency and robustness of the WIGOS LEO component by occupying a different orbital plane*.
CDF-R-ORB-03	**Orbit**	The orbit shall provide global coverage to the instrument.
CDF-R-ORB-04	**Orbit**	The orbit shall enable a single spacecraft to achieve a temporal sampling frequency of 12 hours.
CDF-R-ORB-05	**Orbit**	The orbit shall provide the MS instrument with a swath width greater than 2200 km.
CDF-R-DAT-01	**Data**	All raw sensor data and telemetry shall be transferred from the space segment to the ground segment.
CDF-R-DAT-02	**Data**	The system shall transmit telemetry data to and receive telecommands from the ground segment in all mission phases (deployment, commissioning, operations, and disposal) and spacecraft attitudes.
CDF-R-DAT-03	**Data**	The spacecraft shall be able to operate without ground communications for 0.5 days without loss of sensing capability or raw sensor data.
CDF-R-DAT-04	**Data**	Only authorised users/ground stations shall communicate with the spacecraft for command-and-control and health-monitoring purposes.
CDF-R-DAT-05	**Data**	The space and ground segments shall be operated in accordance with the International Telecommunications Union Radio Regulations (ITU RR) and any applicable national regulations where the downlink system is to be operated.
CDF-R-DAT-06	**Data**	The communications subsystem shall operate with the spacecraft pointing nadir.

ID	Type	Requirement
CDF-R-DAT-07	Data	All communication links shall be designed with a nominal link margin of at least 3 dB.
CDF-R-PWR-01	Power	The EPS shall sustain all planned operations throughout the mission life.
CDF-R-PWR-02	Power	The EPS shall provide adequate voltage to all components.
CDF-R-STR-01	Structural	The spacecraft's mass shall not exceed 193 kg.
CDF-R-STR-02	Structural	The spacecraft shall fit within the volume defined by the maximum allowable envelope of the Standard Electron Fairing throughout the entire launch phase.
CDF-R-PROP-01	Propulsion	The propulsion subsystem shall enable station acquisition during commissioning.
CDF-R-PROP-02	Propulsion	The propulsion subsystem shall enable station-keeping and orbit maintenance throughout the spacecraft's operational life.
CDF-R-PROP-03	Propulsion	The propulsion subsystem shall enable the safe deorbiting of the spacecraft at the end of its operational life.
CDF-R-PROP-04	Propulsion	The propulsion subsystem shall enable collision avoidance manoeuvres.
CDR-R-ADCS-01	Pointing	0.1 GSD / 0.09 deg / 5.7 arcmin

Appendix F Derived Specifications Summary

ID	Type	Specification	Value	Unit
CDF-S-ORB-01	Orbit	Altitude	605.52	km
CDF-S-ORB-02	Orbit	Inclination	97.83	deg
CDF-S-ORB-03	Orbit	Period	96.92	min
CDF-S-ORB-04	Orbit	Repeat Cycle	7	days
CDF-S-ORB-05	Orbit	Recurrence Grid Interval	385.34	km
CDF-S-ORB-06	Orbit	LTAN	05:30	hour
CDF-S-PAYL-01	Payload	Power	130.5 (O), 93.9 (B), 56.4 (T)	W
CDF-S-PAYL-02	Payload	Mass	50.5	kg
CDF-S-PAYL-03	Payload	Volume	600 × 400 × 700	mm^3
CDF-S-PAYL-04	Payload	Data rate	2024 (O), 1400 (B), 560 (T)	kbps
CDF-S-DAT-01	Data	1 second	0.42 (UC) 0.253 (C)	MB
CDF-S-DAT-02	Data	1 hour	1518 (UC) 910.8 (C)	MB
CDF-S-DAT-03	Data	1 day	36.5 (UC) 21.9 (C)	GB
CDF-S-DAT-04	Data	1 month (30.5 days)	1111.2 (UC) 666.7 (C)	GB
CDF-S-DAT-05	Data	1 year	13.0 (UC) 8.0 (C)	TB
CDF-S-DAT-06	Data	Mission life (incl. commissioning)	46.5 (UC) 27.9 (C)	TB
CDF-S-DDL-01	Data downlink	Data volume per day	21.9	GB/Day
CDF-S-DDL-02	Data downlink	Packeting overhead	10%	%
CDF-S-DDL-03	Data downlink	Required data downlink	24.0	GB/Day
CDF-S-DDL-04	Data downlink	Margin	10%	%
CDF-S-DDL-05	Data downlink	Required data downlink with margin	26.4	GB/Day
CDF-S-DDL-06	Data downlink	Architecture	RF direct-to-earth	-

ID	Type	Specification	Value	Unit
CDF-S-DDL-07	Data downlink	Ground station network	Commercial ground station as a service, multiple providers globally	-
CDF-S-DDL-08	Data downlink	Radiocommunications band	X-band	-
CDF-S-DDL-09	Data downlink	Spacecraft antenna type	Isoflux, approximately 60° edge of coverage, circular polarised	-
CDF-S-DDL-10	Data downlink	Ground station antenna type	5.4 m parabolic dish, circularly polarised	-
CDF-S-DDL-11	Data downlink	Modulation and coding type	DVB-S2 QPSK2/5 SRRC(0.35)	-
CDF-S-DDL-12	Data downlink	Power consumption—standby	1	W
CDF-S-DDL-13	Data downlink	Power consumption—transmitting	20	W
CDF-S-DDL-14	Data downlink	Mass estimate	1.5	kg
CDF-S-DDL-15	Data downlink	Cost estimate (no margin)	$265,000	AUD
CDF-S-DDL-16	Data downlink	User data rate	23.7	Mbps
CDF-S-DDL-17	Data downlink	Spectral occupied bandwidth	35.1	MHz
CDF-S-DDL-18	Data downlink	Required data downlink with margin	26.4	GB/day
CDF-S-DDL-19	Data downlink	Radio user data rate	23.7	Mbps
CDF-S-DDL-20	Data downlink	Required downlink time	149	min/day
CDF-S-DDL-21	Data downlink	Downlink duty cycle	10.5	%
CDF-S-DDL-22	Data downlink	Mean number of passes used per day	27	passes/day
CDF-S-DDL-23	Data downlink	Mean duration of passes used	5.6	min/pass
CDF-S-DDL-24	Data downlink	Pass overhead per pass	2	min/pass
CDF-S-DDL-25	Data downlink	Mean billable duration per pass	7.6	min/pass
CDF-S-DDL-26	Data downlink	Mean billable minutes per day	205	min/day
CDF-S-DDL-27	Data downlink	Ground station access cost	3	USD/min
CDF-S-DDL-28	Data downlink	Cost per day	615	USD
CDF-S-DDL-29	Data downlink	Cost per year	225,000	USD
CDF-S-COM-01	TT&C	Power Consumption—Receiving only	3.5	W

ID	Type	Specification	Value	Unit
CDF-S-COM-02	TT&C	Power Consumption—Transmit and Receive	6.8	W
CDF-S-COM-03	TT&C	Transmit Duty Cycle	1	%
CDF-S-COM-04	TT&C	Mass	1.67	kg
CDF-S-COM-05	TT&C	Cost (before margin)	$317,200	AUD
CDF-S-PWR-01	Power	Orbit average power	182.6	W
CDF-S-PWR-02	Power	Solar array area	0.89	m^2
CDF-S-PWR-03	Power	Solar array mass	2.3	kg
CDF-S-PWR-04	Power	Battery capacity	296.4	Wh
CDF-S-PWR-05	Power	Battery mass	3.5	kg
CDF-S-STR-01	Structure	Total spacecraft dry mass	152.9	kg
CDF-S-STR-02	Structure	Total spacecraft wet mass	169.5	kg
CDF-S-STR-03	Structure	Spacecraft volume	0.4	m^3
CDF-S-PROP-01	Propulsion	Propellant mass	16.57	kg
CDF-S-PROP-02	Propulsion	Total delta-V	225.7	m/s
CDF-S-ADCS-01	Attitude	Angular Momentum (N.m.s)	0.517	N.m.s
CDF-S-ADCS-02	Attitude	Torque (N.m)	0.062	N.m
CDF-S-THERM-01	Thermal	Total radiator area	0.4	m^2

References

[1] https://www.nasa.gov/seh/3-project-life-cycle. Accessed 30/01/2023.

[2] Bormann, N., Lawrence, H., & Farnan,J., 2019: Global observing system experiments in the ECMWF assimilation system. ECMWF Technical Memorandum 839, doi: 10.21957/sr184iyz.

[3] Joo, S., Eyre, J. and Marriott, R., 2013. The impact of Metop and other satellite data within the Met Office global NWP system using an adjoint-based sensitivity method. Monthly weather review, 141(10), pp.3331-3342.

[4] S. Brown, B. Lambrigtsen, A. Tanner, J. Oswald, D. Dawson and R. Denning, "Observations of tropical cyclones with a 60, 118 and 183 GHz microwave sounder," 2007 IEEE International Geoscience and Remote Sensing Symposium, Barcelona, Spain, 2007, pp. 3317-3320, doi: 10.1109/IGARSS.2007.4423554.

[5] WMO, 2021. Satellite Data Requirements for Global Numerical Weather Prediction, 2021. Accessed on 20/02/2023 at: https://wmoomm.sharepoint.com/:b:/s/wmocpdb/ERyyLeCEeYdAglNOjHGMW7sBGE4ZG7P-DjVxQ0sGwlvhGg?e=q6C1Pa

[6] WMO, 2020. Vision for the WMO Integrated Global Observing System in 2040. WMO- No. 1243, ISBN: 978-92-63-11243-9. Accessed on 17/02/2023 at: https://library.wmo.int/index.php?lvl=notice_display&id=21716

[7] WMO, 2022. WMO OSCAR/Space Gap Analysis. CGMS Working Paper CGMS-50-WMO-WP-08. Presented at CGMS 50, 13 May 2022. Accessed on 17/02/2023 at: https://www.cgms-info.org/Agendas/GetWpFile.ashx?wid=f2dd9933-2c23-4d5d-9728-9732f833294a&aid=2d91a454-cf12-4551-ad27-0463b323b89f

[8] Inter-Agency Space Debris Coordination Committee (IDAC). (2021). IADC Space Debris Mitigation Guidelines (IADC-02-01 Rev. 3). IADC Steering Group and Working Group 4. https://www.iadc-home.org/documents_public/view/id/172#u

[9] International Organisation for Standardisation. (2016). *Space systems – Estimation of orbit lifetime* (ISO Standard No. 27852:2016). https://www.iso.org/standard/68572.html

[10] WMO. (2022). OSCAR/Space Gap Analysis Tool (2.7) [Software]. Accessed March 1, 2023, at https://space.oscar.wmo.int/gapanalyses

[11] JPSS-1/NOAA-20 (By ESA Committee on Earth Observing Satellites). (2023). eoPortal. Retrieved February 24, 2023, from https://www.eoportal.org/satellite-missions/noaa-20

[12] Jones, E. E., Garrett, K., & Boukabara, S. (2017). Assimilation of Megha-Tropiques SAPHIR Observations in the NOAA Global Model, Monthly Weather Review, 145(9), 3725-3744.

[13] Aires, F., Prigent, C., Orlandi, E., Milz, M., Eriksson, P., Crewell, S., Lin, C.C. and Kangas, V., 2015. Microwave hyperspectral measurements for temperature and humidity atmospheric profiling from satellite: The clear-sky case. Journal of Geophysical Research: Atmospheres, 120(21), pp.11-334.

[14] Blackwell, W.J., Bickmeier, L.J., Leslie, R.V., Pieper, M.L., Samra, J.E., Surussavadee, C. and Upham, C.A., 2010. Hyperspectral microwave atmospheric sounding. IEEE Transactions on Geoscience and Remote Sensing, 49(1), pp.128-142.

[15] Mahfouf, J.F., Birman, C., Aires, F., Prigent, C., Orlandi, E. and Milz, M., 2015. Information content on temperature and water vapour from a hyper-spectral microwave sensor. Quarterly Journal of the Royal Meteorological Society, 141(693), pp.3268-3284.

[16] Aires, F, Prigent, C, Buehler, SA, Eriksson, P, Milz, M, Crewell, S. Towards more realistic hypotheses for the information content analysis of cloudy/precipitating situations – Application to a hyperspectral instrument in the microwave. Q J R Meteorol Soc. 2019; 145: 1– 14.

[17] Gambacorta, A., Stephen, M., Gambini, F., Santanello, J.,Piepmeier, J., Blaisdell, J., Moradi, I., Zhu, Y., McCarty, W., Blumberg, W., Rosenberg, R., Mohammed, P., Sullivan, D., Susskind, J., and Racette, P., 2022, March. The Hyperspectral Microwave Instrument (HyMPI). In GSICS MW Workshop.

[18] Gambacorta, A., Stephen, M., Gambini, F., Santanello, J., Mohammed, P., Sullivan, D., Blaisdell, J., Rosenberg, R., Blumberg, W., Moradi, I. and Zhu, Y., 2022, July. The Hyperspectral Microwave Photonic Instrument (HyMPI)-Advancing Our Understanding of the Earth's Planetary Boundary Layer from Space. In 42nd annual International Geoscience and Remote Sensing Symposium (IGARSS).

[19] https://electronics360.globalspec.com/article/18760/5g-vs-6g-spectrum-comparison

[20] HYMS (HYper-spectral Microwave Sounder): Novel and Critical Component Development and System Bread-boarding. Accessed on 17/02/2023 at: https://ceoi.ac.uk/technologies/passive-microwave/microwave-technologies/hyms-hyper-spectral-microwave-sounder-novel-and-critical-component-development-and-system-bread-boarding/

[21] Aires, F., Prigent, C., Orlandi, E., Milz, M., Eriksson, P., Crewell, S., Lin, C.-C., and Kangas, V. (2015), Microwave hyperspectral measurements for temperature and humidity atmospheric profiling from satellite: The clear-sky case, J. Geophys. Res. Atmos., 120, 11,334– 11,351, doi:10.1002/2015JD023331.

[22] NASA State-of-the-Art of Small Spacecraft Technology 2021 (Section 11.5.3) and ECSS-E-ST-50-05C Rev. 2.

[23] ETSI EN 302 307 V1.2.1 (2009-08) European Standard (Telecommunications series) Digital Video Broadcasting (DVB); Second generation framing structure, channel coding and modulation systems for Broadcasting, Interactive Services, News Gathering and other broadband satellite applications (DVB-S2).

[24] https://www.endurosat.com/cubesat-store/cubesat-communication-modules/x-band-transmitter/

[25] NASA State-of-the-Art of Small Spacecraft Technology 2021 (section 9.5.7).

[26] https://products.beyondgravity.com/d/SVq1aavsDmtE/library/collection/68

[27] http://mdkenny.customer.netspace.net.au/metsat_frequencies-NEW.html

[28] https://aws.amazon.com/ground-station/locations/

[29] https://www.ksat.no/ground-network-services/

[30] https://www.viasat.com/space-innovation/space-and-networking-technology/ground-network/

[31] https://aws.amazon.com/ground-station/pricing/

[32] https://www.rocketlabusa.com/assets/Uploads/Frontier-S-S300179-v1.1.pdf

[33] https://endurosat.com/cubesat-store/cubesat-antennas/s-band-antenna-commercial/

[34] https://www.spectrolab.com/photovoltaics/XTJ-CIC_Data_Sheet.pdf

[35] https://sparkwing.space/download-sparkwing-data-sheet-pdf/

[36] Rocket Lab Electron Payload User Guide. https://www.rocketlabusa.com/assets/Uploads/Payload-User-Guide-LAUNCH-V6.6.pdf Accessed 03/12/2022.

[37] Average mass as a subsystem as a percentage of dry mass for LEO with propulsion spacecraft. Table 14-18. Space Mission Engineering: The New SMAD (2011).

[38] Votel, R., Sinclair, D., (2012), Comparison of Control Moment Gyros and Reaction Wheels for Small Earth-Observing Satellites, 26th Annual AIAA/USU Conference on Small Satellites

[39] Letcher, T., & Vallero, D. (Eds.). (2019). Waste: A handbook for management, Chapter 30: Space Waste. Academic Press. pp 567-583.

[40] King et al. (2008), Small Satellite LEO Maneuvers with Low-Power Electric Propulsion

[41] NASA, (2021), Small Spacecraft State of the Art, pp 58 – 62.

[42] https://airbusus.com/wp-content/uploads/2021/06/ARROW_Brochure-US-06.28.21.pdf

[43] Wertz, J. R., Everett, D. F., & Puschell, J. J. (2011). Space mission engineering : the new SMAD. Microcosm Press : Sold and distributed worldwide by Microcosm Astronautics Books, pp 566-567

[44] https://inspace.anu.edu.au/nstf

[45] https://everydayastronaut.com/transporter-2-falcon-9-block-5/

[46] The Australian Communications and Media Authority. (2012). Australian procedures for the coordination and notification of satellite systems. https://www.acma.gov.au/publications/2012-01/guide/australian-procedures-coordination-notification-satellite-systems

[47] Risk Classification for NASA Payloads, NASA Procedural Requirements NPR 8705.4A, April 29, 2021. Accessed on 23/02/2023 at: https://nodis3.gsfc.nasa.gov/npg_img/N_PR_8705_004A_/N_PR_8705_004A_.pdf

[48] NASA Systems Engineering Processes and Requirements, NASA Procedural Requirements, NPR 7123.1C, February 14, 2020.

[49] Mrozinski, J. et al., "NASA Instrument Cost Model: Impact of Mission Class on Cost", NASA Cost Symposium-August 2016, Jet Propulsion Laboratory, California Institute of Technology (2016).

[50] Hahn, M., "Higher fidelity estimating: Program management, systems engineering and mission assurance", NASA Cost Symposium August 25, 2015, NASA Ames Research Center (2015).

[51] https://www.ato.gov.au/Rates/Foreign-exchange-rates/

[52] NASA State-of-the-Art of Small Spacecraft Technology 2021 (Table 9-8)

[53] Ostojic, K., Cahill, F., Henry, M., Huggard, P., Brooke, T., & Mann, J. (2021, July). Blackbody Calibration Targets for the Microwave Sounder Instruments: Control Methods and Modelling Techniques. 50th International Conference on Environmental Systems.

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